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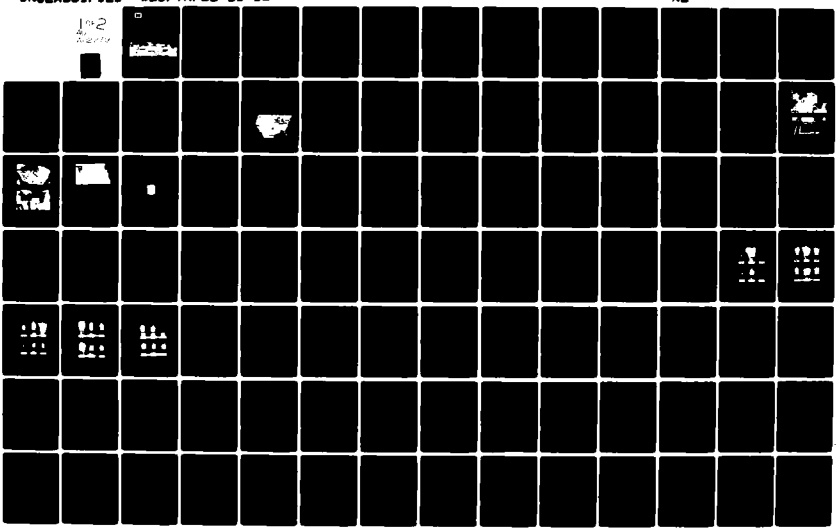

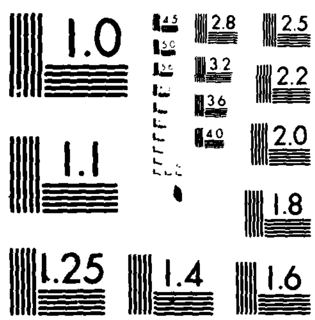

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TECHNICAL REPORT EL-81-12

INFLUENCE OF DISPOSAL ENVIRONMENT ON AVAILABILITY AND PLANT UPTAKE OF HEAVY METALS IN DREDGED MATERIAL

by

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Final Report

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Heavy metal uptake by *Cyperus esculentus* from 15 highly contaminated freshwater sediments under reduced (flooded) and oxidized (upland) disposal conditions was investigated in the greenhouse. Heavy metal uptake by *Spartina alterniflora* and *Distichlis spicata* from 14 highly contaminated saltwater sediments under flooded disposal conditions was also investigated in the greenhouse. The freshwater sediments were collected from waterways in the Great

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20. ABSTRACT (Continued).

Lakes area; the saltwater sediments were collected from the gulf and Atlantic coastal areas. The sediments were transported to the laboratory, where each sediment was mixed thoroughly and divided in half. One half of the sediment was potted and maintained in a flooded state; the other half was air dried and ground before being potted (upland condition). *Cyperus esculentus* was grown from tubers planted in the freshwater sediments. Seeds of *S. alterniflora* and *D. spicata* were planted in the saltwater sediments. All plants were allowed to grow to maximum vegetative yield (*C. esculentus*, 90 days; *S. alterniflora* and *D. spicata*, 131 days). The moisture content of the upland sediments was maintained between field capacity of the sediment and wilting point of the plant.

The plants were harvested and analyzed for the heavy metals zinc, cadmium, copper, iron, manganese, arsenic, mercury, nickel, chromium, and lead. The sediments were analyzed for total heavy metals, diethylene triamine pentaacetic acid (DTPA) extractable heavy metals, heavy metals in the sediment interstitial water, oil and grease, pH, calcium carbonate equivalent, total sulfur, total phosphorus, total Kjeldahl nitrogen, and organic matter.

Air drying the sediments resulted in increased DTPA extractable and interstitial water heavy metals. Plant uptake of heavy metals, especially zinc and cadmium, was shown to be greater in plants grown in upland sediments compared with flooded sediments. Relationships between sediment chemical and physical characteristics and plant content of heavy metals were investigated. Plant yield was shown to be an important factor in determining plant uptake of heavy metals.

Since the results of this investigation showed that plant uptake of heavy metals was site specific, it is recommended that a plant bioassay be performed on the sediments in question to determine the availability of heavy metals contained in sediments. Results of the plant bioassay will assist CE District personnel in making environmentally informed decisions on dredged material disposal alternatives.

PREFACE

This study was conducted at the U. S. Army Engineer Waterways Experiment Station (WES) during June 1977 to September 1980 by personnel of the Contaminant Mobility Research Team: Drs. Bobby L. Folsom, Jr., and Charles R. Lee; Messrs. D. J. Bates, D. W. Jackson, D. E. Wilkerson, John L. Grace, III, and M. L. Richter; and Ms. Helen Benet. The study was under the general supervision of Dr. R. M. Engler, Chief, Ecological Effects and Regulatory Criteria Group, Dr. R. L. Eley, Chief, Ecosystem Research and Simulation Division (ERSD), and Dr. J. Harrison, Chief, Environmental Laboratory. Assistance was also received from several other members of the ERSD. Funding for the study was provided by the Dredging Operations Technical Support Program (DOTS), Mr. C. C. Calhoun, Program Manager.

Dr. C. B. Loadholt, Professor of Biometrics, Medical College of South Carolina, assisted the authors on statistical matters. Dr. W. H. Patrick, Jr., Professor of Marine Science, Louisiana State University; Dr. F. T. Bingham, Professor of Soil Chemistry, University of California, Riverside; and Dr. N. R. Page, former Head of Agricultural Chemical Services, Clemson University; Dr. W. L. Berry, University of California, Los Angeles; Ms. A. Mudroch, Canada Centre for Inland Waters, Burlington, Ontario; Dr. B. E. Davies, University College of Wales, Aberystwyth, Wales; Dr. D. T. Tingey, U. S. Environmental Protection Agency, Corvallis, Oreg.; Dr. W. vanDriel, Institute for Soil Fertility, Groningen, The Netherlands; Dr. J. L. Gallagher, University of Delaware; and Dr. P. J. Peterson, Westfield College, London, England; are acknowledged for their review of this report.

Appreciation for assistance in sediment collection is expressed to Mr. Paul W. Atkinson and the crew of the derrick boat, HURON, and the Captain and crew of the tug, AUSABLE, U. S. Army Engineer District, Detroit; Messrs. R. Mondelius and R. Peterson, Kewannee Project Office, U. S. Army Engineer District, Chicago; Mr. E. Swift, U. S. Army Engineer Division, New England; Mr. G. Perry, U. S. Army Engineer District, San Francisco; Mr. C. Holmes, U. S. Geological Survey, Corpus Christi,

Tex.; Mr. J. Gerwald, Shortline Community College, Seattle, Wash.; and Mr. O. Bricker, Maryland Geological Survey, Baltimore, Md.

Commanders and Directors of the WES during the study were COL John L. Cannon, CE, and COL Nelson P. Conover, CE. Technical Director was Mr. F. R. Brown.

This report should be cited as follows:

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INFLUENCE OF DISPOSAL ENVIRONMENT ON AVAILABILITY AND PLANT UPTAKE OF HEAVY METALS IN DREDGED MATERIAL

PART I: INTRODUCTION

Background

1. The volume of sediment that must be removed yearly to maintain navigation in the waterways of the United States is estimated to be 229 million cubic metres (U. S. Army Corps of Engineers Water Resources Support Center 1979). Toxic metals, pesticides, organic wastes, nutrients, etc., can move into the waterways as a result of land drainage and uncontrolled waste disposal. Many of these contaminants become associated with suspended solids and can accumulate in the sediments at the bottom of the waterways. The availability or release of contaminants from sediments has been shown to be controlled by the degree of oxidation that occurs (Gambrell et al. 1977).

2. Guidelines based on available literature and laboratory studies have been formulated to assist in selecting disposal alternatives for contaminated dredged material to minimize adverse environmental effects (Gambrell, Khalid, and Patrick 1978). While these guidelines give adequate general management schemes, there is still a need to be able to test, on a case-by-case basis, the potential availability of dredged material contaminants under various disposal environments.

3. There are essentially three alternative environmental conditions for the disposal of dredged material: open water, intertidal, and upland. Open water disposal has been extensively used as a convenient and relatively inexpensive means of disposal (Center for Wetland Resources 1977). This disposal alternative results in the sediment being exposed to oxidizing conditions for only a limited time during dredging and transport. Consequently, the sediment reverts to its original reduced state. Intertidal placement of dredged sediment or use of dredged sediment to

create marshes has gained increased attention since the completion of the Dredged Material Research Program (DMRP) of the U. S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Miss. This disposal alternative allows the reduced sediment to undergo a limited amount of oxidation, mainly at the sediment surface (sediment-water interface). Upland disposal is the deposition of dredged material in a situation where the sediment is allowed to drain, dry out, and oxidize completely. Frequently, this includes the deposition of dredged sediment within a diked confinement. Other examples of upland disposal are the placement and incorporation of dredged material into dry, agriculturally oriented land (Gupta et al. 1978), as a covering on sanitary landfills, and in acid mine spoil reclamation.

4. At present, certain sediments have been designated as highly polluted (U. S. Environmental Protection Agency 1975a, 1975b; Johanson and Johnson 1976). Therefore, in order to make environmentally informed decisions on which disposal alternative to use for contaminated dredged sediment, it becomes necessary to have an estimate of the relative availability of the contaminants in a proposed dredged sediment under each disposal alternative.

Scope of Work

5. A study of the solubility, availability, and plant uptake of the heavy metals zinc (Zn), cadmium (Cd), copper (Cu), arsenic (As), mercury (Hg), iron (Fe), manganese (Mn), nickel (Ni), chromium (Cr), and lead (Pb) was conducted under two extremes of oxidation-reduction condition: reduced (flooded) and oxidized (upland) in freshwater sediments. The study of the solubility and plant availability of the metals on saltwater sediments was limited to only the flooded condition. When the saltwater sediments were air dried, interstitial water salinities exceeded 90 parts per thousand (ppt), above which plants will not survive.

6. The specific objectives of this study were to determine the following:

<u>a</u>. The influence of placing dredged material in flooded and

upland conditions (air drying) on diethylene triamine pentaacetic acid (DTPA) extractable heavy metals (a measure of availability).

b. The differences in heavy metal uptake from freshwater sediments by freshwater plants grown under flooded and upland conditions.

c. The differences in plant uptake of heavy metals from saltwater sediments between two saltwater marsh plant species.

d. The relationship of plant uptake of selected heavy metals and sediment characteristics such as total heavy metal content, DTPA extractable metals, organic material content, sulfur, oil and grease, nitrogen (N), phosphorus (P), particle size, etc.

PART II: METHODS AND MATERIALS

Field Techniques

Sediment selection

7. Ten of the most highly contaminated sediments in the United States were selected according to available published literature (Johanson and Johnson 1976; U. S. Environmental Protection Agency 1975a, 1975b; Brannon, Plumb, and Smith 1978). Figure 1 illustrates the geographical locations sampled. Locations of the saltwater sediments were Bridgeport Harbor, Conn.; Baltimore Harbor, Md.; Corpus Christi Ship Channel, Tex.; Oakland Inner Harbor, Calif.; and Duwamish Waterway, Seattle, Wash. Actual sample sites within each location are illustrated in Figures 2-4. Locations of the freshwater sediments were Detroit River, Mich.; Michigan City Harbor, Ind.; Indiana Harbor, Ind.; Menominee River, Wis.-Mich.; and Milwaukee Harbor, Wis. The actual sampling sites at each location are

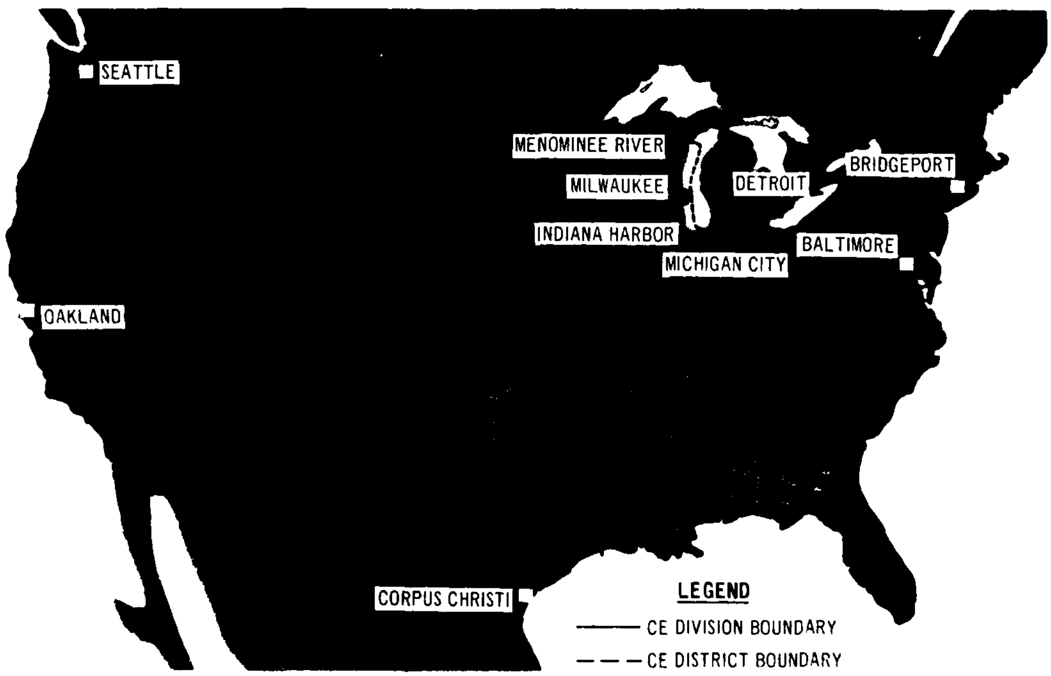


Figure 1. Sediment sample locations for marsh plant-heavy metal uptake study

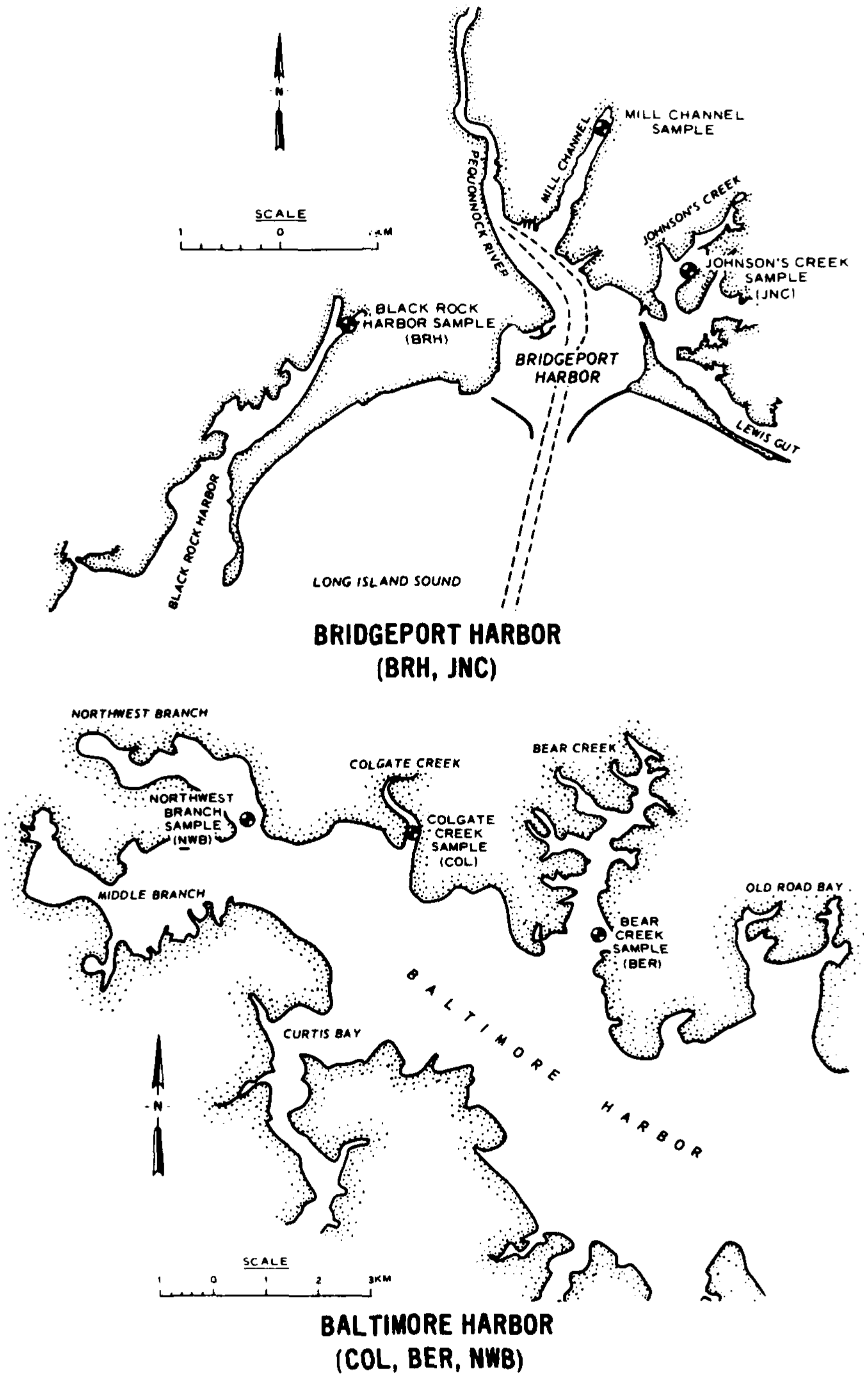
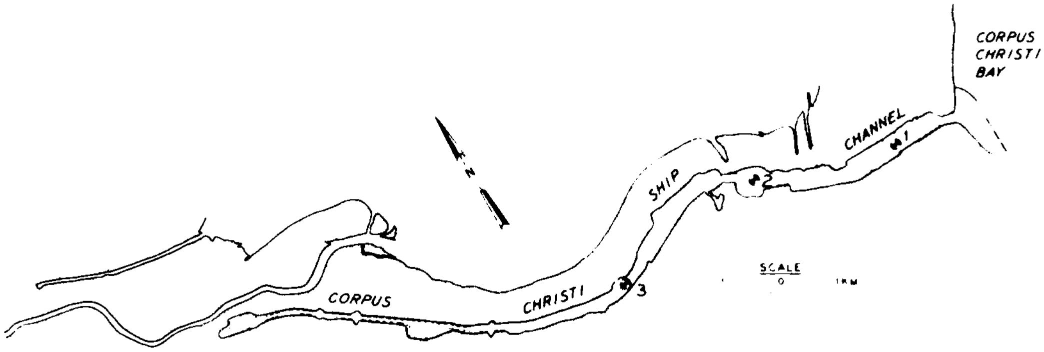
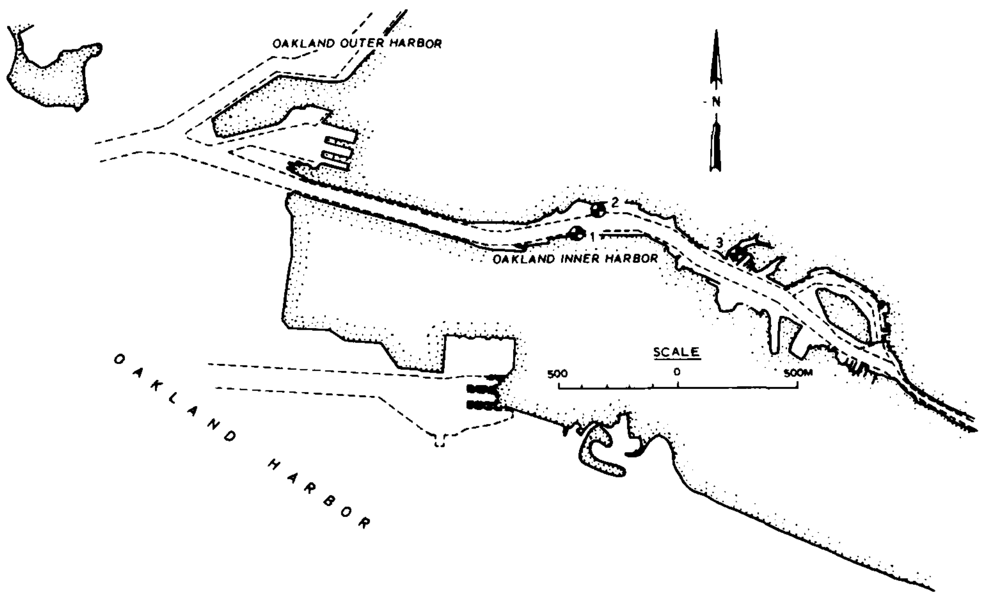


Figure 2. Saltwater sediment sampling locations at Bridgeport Harbor (BRH and JNC), Conn., and Baltimore Harbor (COL, BER, and NWB), Md.

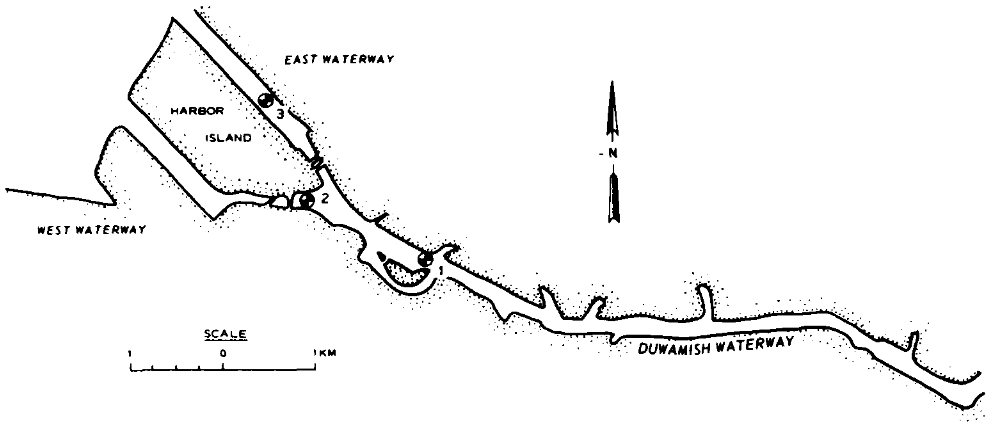


CORPUS CHRISTI SHIP CHANNEL
(CC)



OAKLAND HARBOR
(OH)

Figure 3. Sediment sampling locations at Corpus Christi (CC), Tex., and Oakland Inner Harbor (OH), Calif.



SEATTLE-DUWAMISH WATERWAY
(SE)

Figure 4. Saltwater sediment sampling locations at Seattle (SE), Wash.

illustrated in Figures 5-7. Three sediment samples were taken at each of the 10 locations. The sampling sites ranged in location from near known sources of contamination to some distance away from the source. This array of sampling resulted in a range of metal concentrations in the sediment samples and also expedited sediment collection.

Sampling and handling

8. Sediments were collected during June 1977 with clamshell or similar sampler. One 208-ℓ steel drum (55 gal) from each site provided a sufficient quantity of sediment to conduct the study. The drums were sealed with airtight lids and transported by commercial truck to the WES. No precaution was taken to protect the drums from temperature extremes. The drums were delivered to the WES within 14 days after collection. No precaution was taken to protect the sediment from contamination from the walls of the drums because the drums were new and contamination should have been negligible, especially in view of the large volume to wall surface ratio.

Greenhouse Techniques

General experimental design

9. The general experimental design is represented in Figure 8

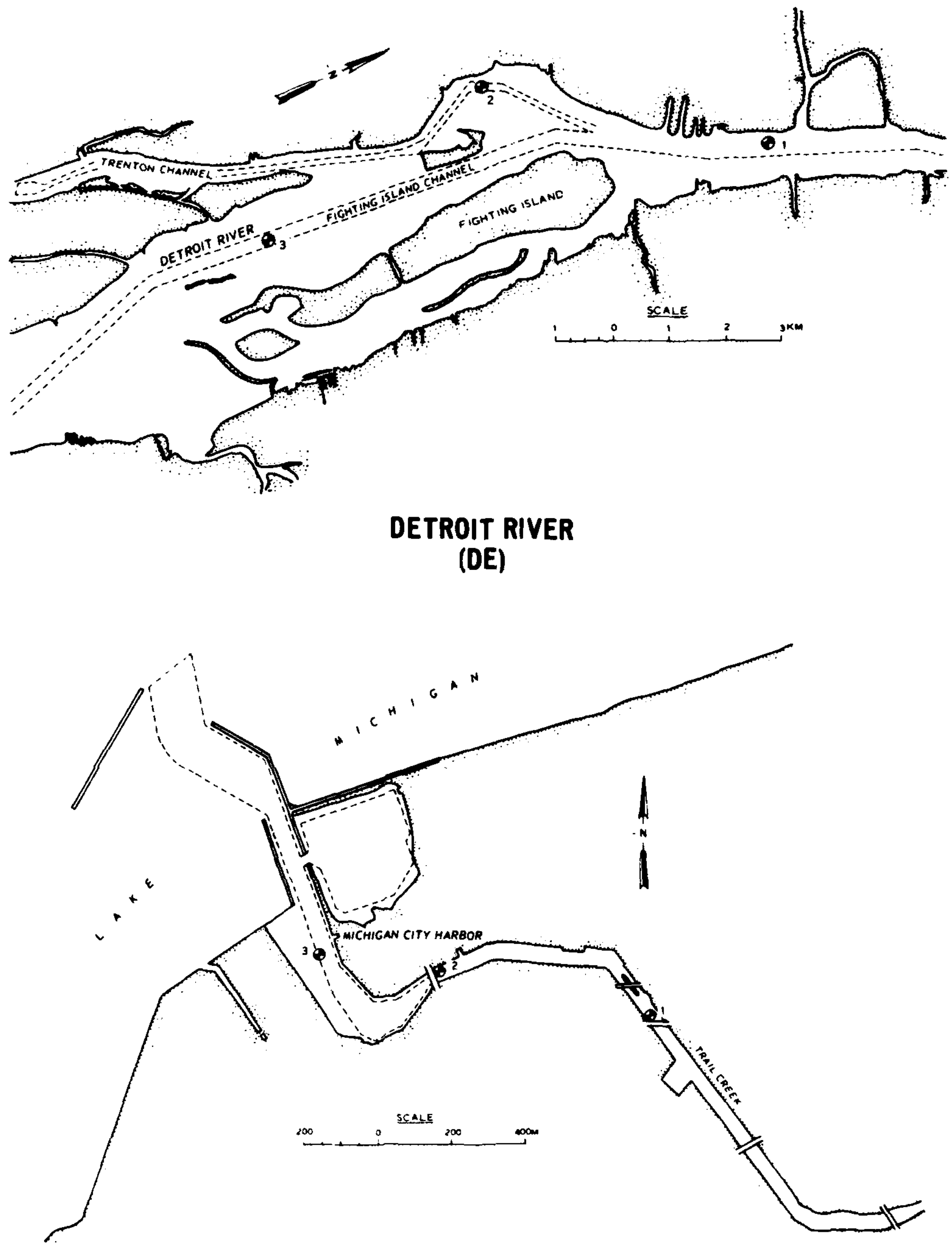
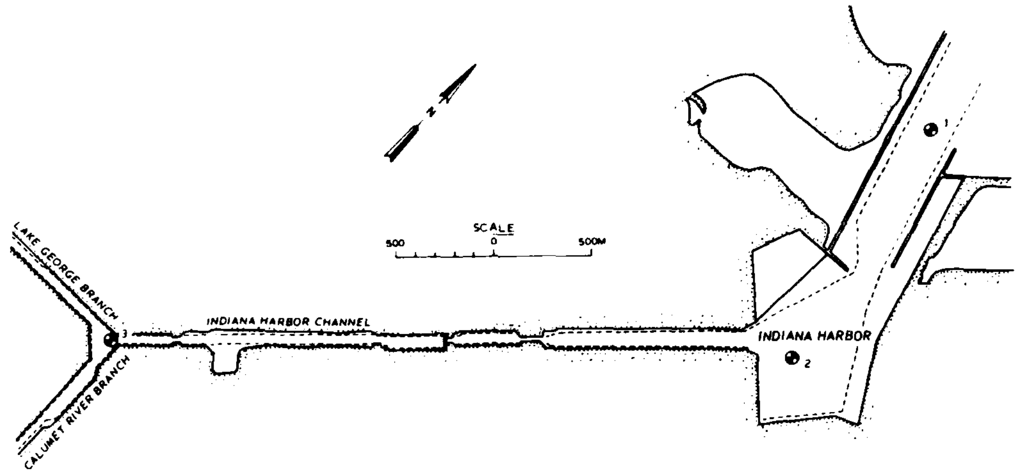
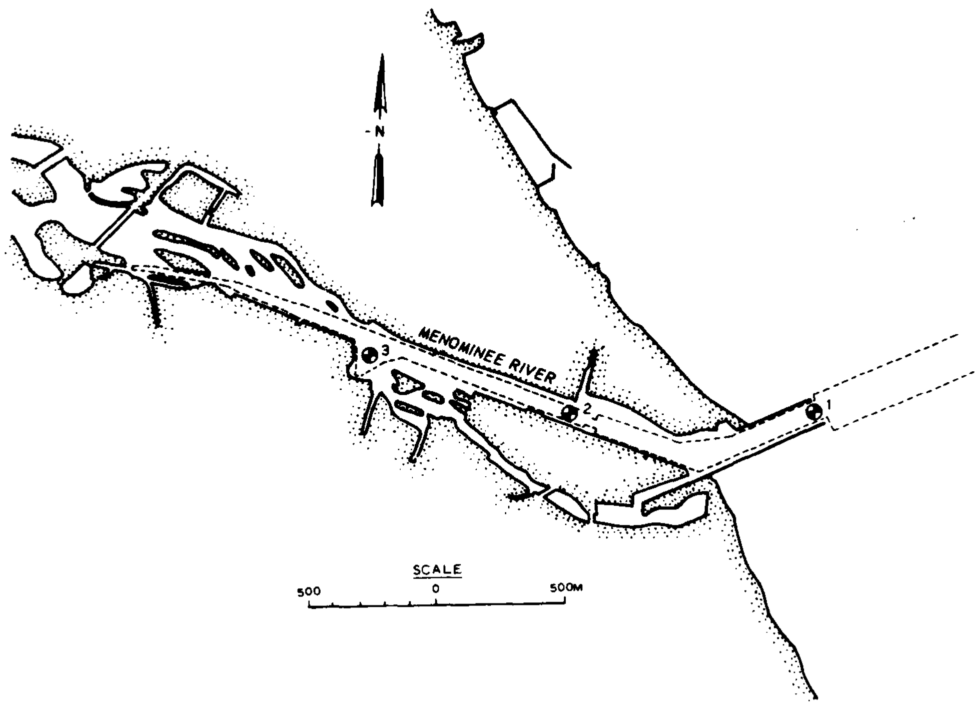


Figure 5. Freshwater sediment sampling locations at Detroit (DE), Mich., and Michigan City (MC) Harbor, Ind.

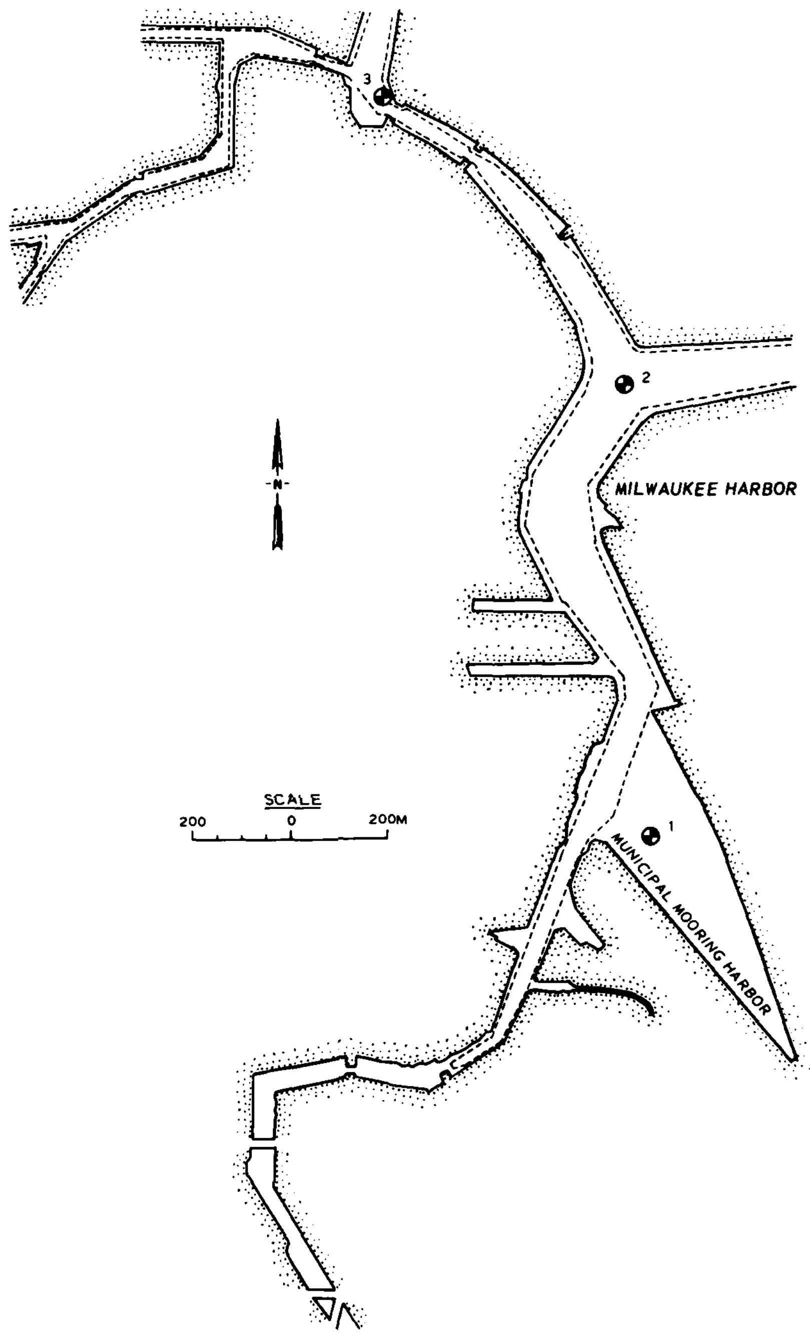


INDIANA HARBOR
(IN)



MENOMINEE RIVER
(ME)

Figure 6. Freshwater sediment sampling locations at Indiana Harbor (IN), Ind., and Menominee River (ME), Wis.



MILWAUKEE HARBOR
(MW)

Figure 7. Freshwater sediment sampling location at Milwaukee Harbor (MW), Wis.

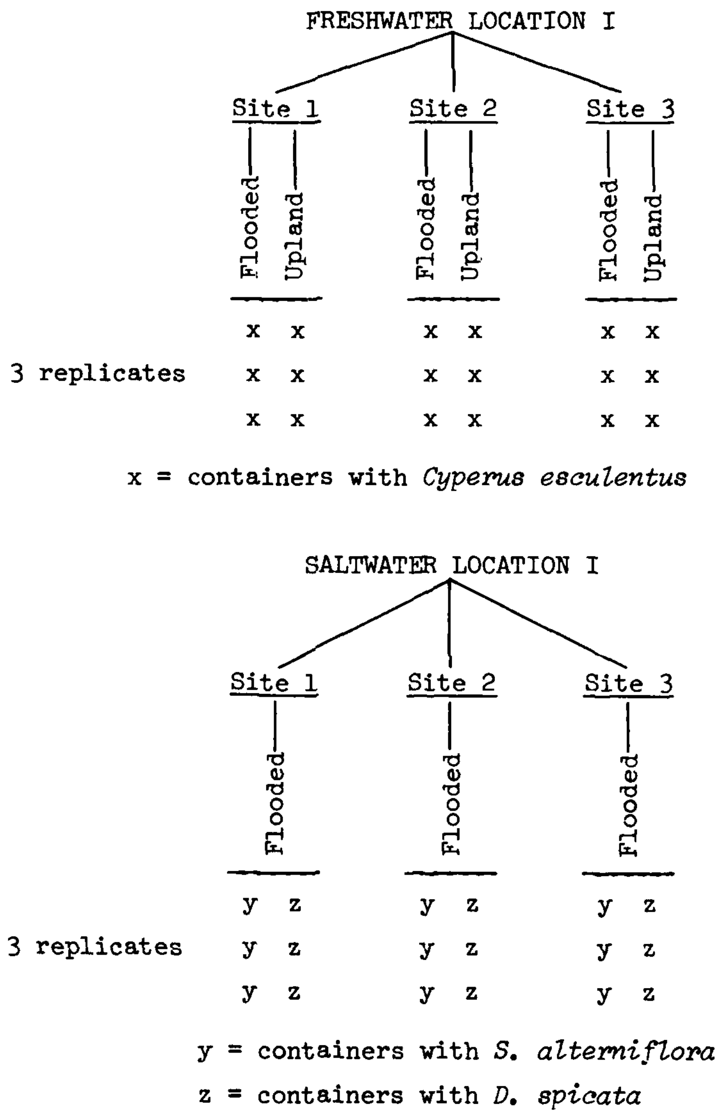


Figure 8. Schematic representation of the general experimental design for each of five freshwater and five saltwater locations

and contains the following major points:

a. There were five general locations, each with three sites, for both freshwater and saltwater sediments.

b. There were two disposal conditions for each freshwater sediment (flooded and upland) and one disposal condition for each saltwater sediment (flooded).

c. Each freshwater sediment was planted with one plant species (*Cyperus esculentus*). Each saltwater sediment was planted with two plant species (*Spartina alterniflora* and *Distichlis spicata*).

d. Each experimental unit (plant/sediment combination) was replicated three times.

e. There were 180 total experimental units--90 freshwater (45 flooded and 45 upland) and 90 saltwater (45 *S. alterniflora* and 45 *D. spicata*).

Sediment preparation

10. The sediments were mixed while in their drums with a Lightnin Mixer, Model No. D-2 (Mixing Equipment, Inc., 199 Mt. Read Blvd., Rochester, N.Y. 14604) upon arrival at the WES. The mixer was raised and lowered to thoroughly mix the sediments contained in each drum (Figure 9). After mixing the sediments, three 7.57-ℓ (8-qt) Bain-Marie buckets were filled with each sediment and capped with the included lid to maintain flooded conditions until time of planting. Three 1-ℓ plastic sample bottles were filled with each sediment for subsequent physical and chemical analyses.

11. After the buckets had been filled, approximately one-half drum of the wet sediment was placed into 2-m × 2-m × 14-cm wooden drying flats lined with a sheet of polyethylene (Figure 10). The drying flats containing the sediments were situated on the floor of the greenhouse so that they were protected from the weather, dust, etc. The sediment was turned daily so that it dried as evenly as possible (Figure 11).

12. The air-dried sediments were subsequently ground in a Kelly Duplex grinder (The Duplex Mill and Manufacturing Company, Springfield, Ohio) to pass a 2-mm screen (Figures 12 and 13).

13. The same quantity of sediment, on an oven-dry weight basis, was used for both the flooded condition and the air-dried (upland-oxidized) condition.

Figure 9. Sediments mixed with a Lightnin Mixer

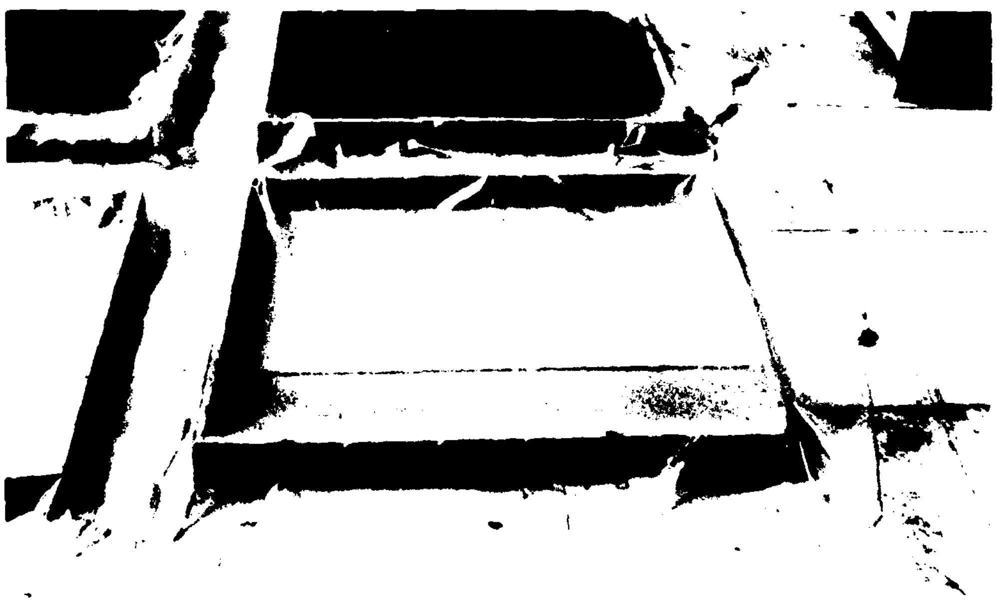


Figure 10. Wet sediment placed in wooden drying flats lined with sheet of polyethylene to dry

Figure 11. Closeup of air-dried sediment before grinding

Figure 12. Kelly grinder used to grind the air-dried sediment

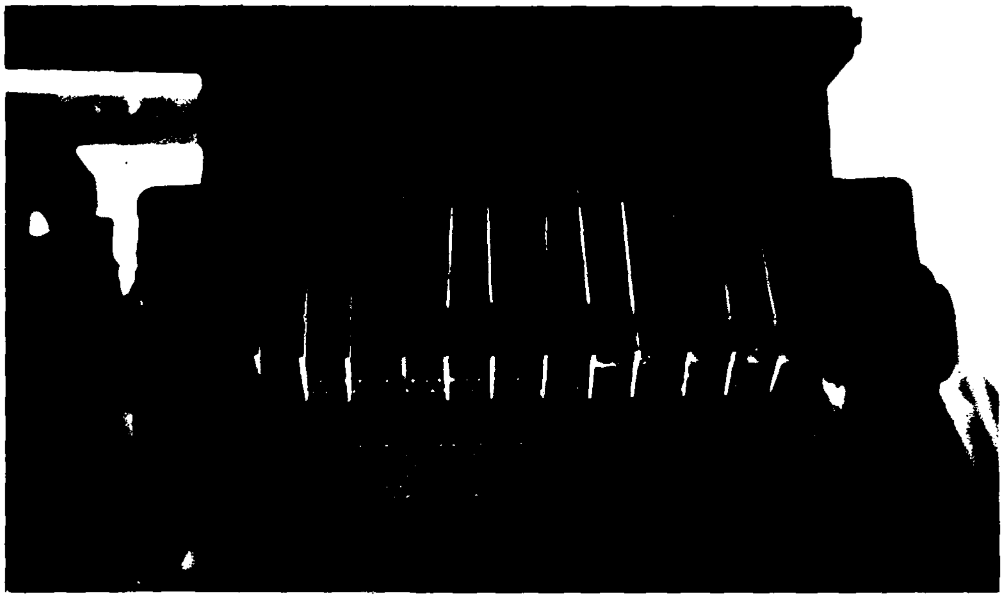


Figure 13. Closeup view of the flailing arms and screen of the Kelly grinder

Experimental unit

14. A schematic diagram of the experimental container is shown in Figure 14. A small inner container rested on polyvinyl chloride (PVC) pipe inside a larger outer container. Eight 6.35-mm-diam holes were drilled in the bottom of the small container; these were covered with a polyethylene sponge overlaid with a layer of washed sand. The sand and sponge acted as a filter to keep the sediment from draining out the bottom of the small container. The holes in the small container allowed water movement into and out of the sediment.

15. After sediment had been placed into the container, a porous plastic filter candle (Porex Materials, Fairburn, Ga.) and a bright platinum electrode were each inserted into the sediment respectively for the withdrawal of interstitial water and measurement of oxidation-reduction potential.

Water supply

16. The source of water used in both experiments was deionized water obtained from a Continental Model 3230 Reverse Osmosis (RO) water system.

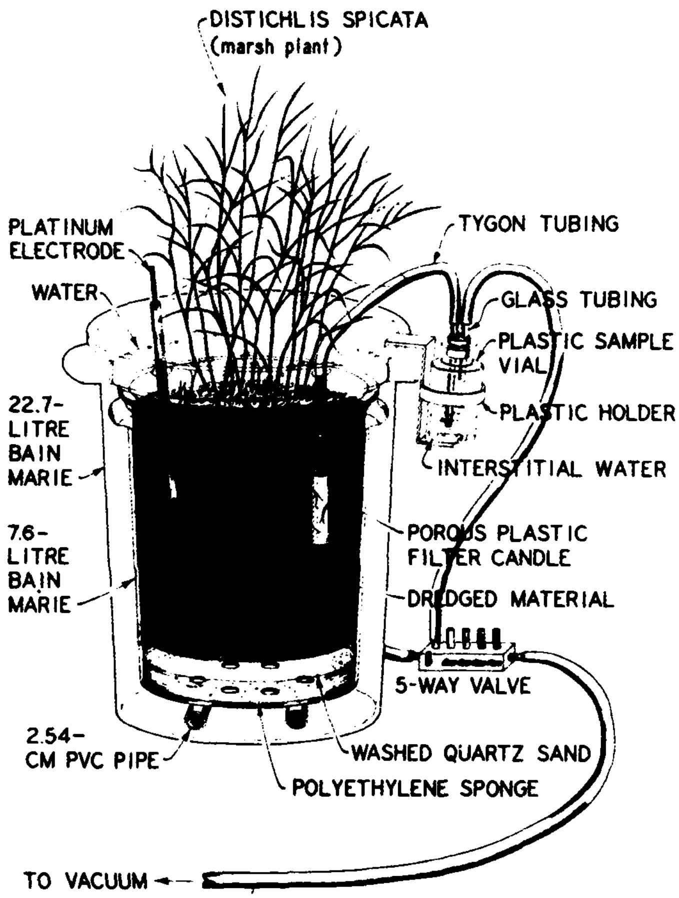


Figure 14. Schematic of the experimental unit used in the study

Insect control

17. Aphid and other insect control was accomplished using the manufacturer's recommended rates of nicotine sulfate liquid spray (Black Leaf 40, Black Leaf Products Co., Elgin, Ill.).

Greenhouse environment

18. The plant growth portion of the study was conducted from June 1977 to November 1977. The temperature regime of the greenhouse was maintained at 38°C daytime maximum and 27°C nighttime minimum from 16 June 1977 to 16 October 1977; it was then changed to 24°C daytime maximum and 16°C nighttime minimum from 17 October to harvest on 12 November 1977.

Freshwater Experiment

Sediment disposal condition

19. Flooded. For the flooded regime, the sediments were not allowed to drain or the surface to dry out. At least a 5-cm depth of water was maintained over the surface of the sediments by addition of RO water as needed.

20. Upland. The moisture content of the upland-oxidized sediments was maintained between field capacity (moisture content at 1/3 bar) and the wilting point of the plant (moisture content at 15 bar tension) as determined by the oxidation-reduction (redox) potential of each sediment, the visual observation of each plant's turgor pressure, and the wetness to feel of each sediment. When watering was necessary, the procedure was as follows: the water level in the outer pot was brought up to the level of sediment in the inner pot and allowed to stand for 2 hr. During this time, water entered the sediment through holes in the bottom of the inner container (Figure 14). After 2 hr, the water was completely siphoned out of the large container and the water in the sediment was allowed to drain out the holes in the bottom of the inner container.

Plants

21. Species. *Cyperus esculentus* var. *sativus* (common name chufa)

was selected for study because it had been shown to take up heavy metals from hydroponic solution cultures (Lee, Sturgis, and Landin 1976) and had potential as a species for marsh plant development with dredged material in freshwater environments. *Cyperus esculentus* was grown from tubers obtained from Wildlife Nurseries, Oshkosh, Wis.

22. Planting, growing, and harvesting techniques. Three pre-sprouted *C. esculentus* tubers were planted in each container of freshwater sediment and allowed to attain maximum vegetative growth (90 days from planting). Approximately 40 days after planting, the leaves of some of the plants began to show signs of early senescence. The dead leaves were collected as they occurred and were subsequently dried to constant weight at 104°C. Collection of the dead leaves proceeded throughout the rest of the experiment. The plants were then harvested and separated into aboveground live, aboveground dead, belowground tubers, and roots. The plant material was rinsed with RO water, blotted with paper towels, dried to constant weight at 104°C, and ground into a coarse powder with a Wiley mill (Model No. 4).

Sediment redox

23. Oxidation-reduction (redox) potentials of the sediments were measured with bright platinum Eh electrodes constructed by the method of Mann and Stolzy (1972) and were cleaned with 6 M hydrochloric acid before placement into the sediment. Electrode equilibration time before measurement was 24 hr. Measurements were made every other day on both flooded and upland sediments during the first 3 weeks of plant growth. During this period, the redox potential of the flooded sediments did not vary more than a few millivolts. Consequently, the redox potential was monitored daily in the upland sediments and weekly in the flooded sediments. All redox measurements were corrected for the reference electrode (-242 mV, saturated potassium chloride calomel electrode).

Solution samples

24. Sediment interstitial water (IW) from the flooded containers was taken three times: initially, in the middle, and at the end (final) of the growth period. Initial IW samples were obtained by centrifuging (13,701 × g) some of the original flooded sediments and decanting the

supernatant. The middle and final IW samples were taken from each flooded pot using a modified method of Hossner and Phillips (1973) in that the porous plastic plug was inserted vertically into the sediment and not inserted through a hole in the side of the plastic bucket.

Saltwater Experiment

Sediment disposal condition

25. Preparation of the saltwater sediments was conducted in the same manner as the freshwater sediments except for the following: sediment IW salinity was measured initially and at daily intervals. Centrifugation was used to separate IW from sediment. Salinity was measured using a refractometer (Model No. 1049, American Optical, Buffalo, N. Y.) until IW could no longer be obtained. Salinity values of the IW ranged from approximately 90 to well over 100 ppt. Available literature indicated that *S. alterniflora* would not grow at IW salinities of greater than 45 ppt (Woodhouse, Seneca, and Broome 1972). In addition, Smith (1970) suggested that high salinity was responsible for *Spartina* dieback in some Louisiana marshes and Adams (1963) suggested that no saltwater marsh plants will survive at IW salinities greater than 70 to 80 ppt. Therefore, the upland-oxidized portion of the saltwater experiment was discontinued.

26. The water used in the saltwater environment was maintained at a salinity of 15 ppt using Instant Ocean (Aquarium Systems, Inc., Eastland, Ohio). The salinity of the floodwater in the saltwater containers was measured daily by using a refractometer. If the salinity of the floodwater increased, then RO water was added to reduce the salinity to 15 ppt. If the salinity decreased, then a portion of the original solution was replaced with enough 15 ppt stock solution to increase the total salinity to 15 ppt. This usually occurred every 4 to 5 days. The saltwater solution was replaced with freshly prepared 15 ppt salinity solution after the initial 4 weeks of growth and at biweekly intervals thereafter to help maintain salinity.

Plants

27. Species. *Spartina alterniflora* (common name cordgrass) and

Distichlis spicata (common name saltgrass) were selected for the study because they had been shown to be salt tolerant and had been grown successfully from seed (Barko and Smart 1976). These species were also shown to take up heavy metals from hydroponic solution culture (Lee, Sturgis, and Landin 1976). In addition, both species had potential for marsh development on dredged material (Barko and Smart 1976). Seed of each species was obtained from Environmental Concern, Inc., St. Michael's, Md.

28. Planting, growing, and harvesting techniques. Seeds of *S. alterniflora* and *D. spicata* were germinated in 15 ppt salinity water. Twenty germinated seedlings were gently placed with the shoot end up into the sediment. A 5-cm layer of 15 ppt salinity water was maintained over the seedlings. After 2 weeks, the plants were thinned to five *S. alterniflora* and ten *D. spicata* per pot. The 5-cm layer of 15 ppt salinity water was maintained over the surface of the sediment until harvest.

29. The plants were allowed to attain maximum vegetative growth (138 days from planting for *S. alterniflora* and 131 days for *D. spicata*).

30. Salt secreted by the leaves of *S. alterniflora* was rinsed off weekly by spraying plant leaves with RO water. The plants were harvested at maximum vegetative production of each species. Plant material was separated into aboveground live, aboveground dead, and belowground portions. The plant material was rinsed with RO water, blotted with paper towels, dried at 104°C until constant weight, and ground into a coarse powder with a Wiley mill.

Sediment redox

31. Redox status of the sediments was measured every other day on the first replicate from each sediment for the first 3 weeks of plant growth. During this period, the redox potential of the sediments did not vary more than a few millivolts. The electrodes were removed from the saltwater sediments, cleaned with 6 M hydrochloric acid, and placed into freshwater sediments as mentioned previously. One week before harvest of plants on the saltwater sediments, the electrodes were removed, cleaned with 6 M hydrochloric acid, and placed back into the flooded saltwater

sediments. After a 24-hr equilibration period, redox was measured to verify that significant change had not occurred since the initial 3 weeks.

Solution samples

32. Interstitial water samples were taken from the saltwater sediments as described for the freshwater sediments.

Laboratory Procedures

Chemical analysis of plant material

33. The instruments and detection limits of the chemical parameters determined are listed in Table 1. Plant materials from only the aboveground live portion of the three species plus tubers from *C. esculentus* were analyzed for total Kjeldahl nitrogen (TKN), phosphorus, and the metals zinc, cadmium, copper, mercury, iron, manganese, arsenic, nickel, chromium, and lead. Sodium and potassium were determined on *D. spicata* and *S. alterniflora* tissues in addition to those elements listed above.

34. Total Kjeldahl nitrogen (TKN) digestion. Total Kjeldahl nitrogen was determined by a modification of Bremner's method (Bremner 1965). The digestion procedure described measures total combined nitrogen plus free ammoniacal nitrogen; hence, a reducing agent was added to include nitrate nitrogen. The proceudre used was as follows: oven-dried and ground plant material (0.5 g) was placed into a dry 100-ml micro-Kjeldahl flask, and 10 ml of RO water was added. The flask was swirled until the plant tissue was evenly distributed in the bulb of the flask and then allowed to stand for 30 min. One gram of potassium sulfate (K_2SO_4), 0.1 g cupric sulfate ($CuSO_4 \cdot 5H_2O$), 0.01 g selenium (Se), and 3.0 ml concentrated sulfuric acid (reagent grade, American Chemical Society (ACS) certified) were added to the flask. The flask was heated cautiously on a digestion stand until frothing had ceased. The heat was increased until the mixture cleared. The mixture was allowed to boil gently until a bluish-green color had formed. The heat was then turned off and the solution allowed to cool to room temperature. The contents of the flask were transferred quantitatively into a 100-ml volumetric

Table 1

Techniques Used in the Analysis of Water, DTPA Extracts, and Nitric Acid and TKN Digests

Chemical Species	Procedures and/or Instrumentation	Lowest Reporting Concentration $\mu g\ g^{-1}$
Zn*	Determined with a Spectrametrics Argon Plasma Emission Spectrophotometer Model II	0.1
Cd*		0.1
Cu*		0.1
Fe*		0.1
Mn*		0.1
Ni*		0.1
Cr*		0.1
Pb*		0.1
K	Perkin-Elmer Model 306 Flame Photometer	1
Na	Same as K	1
As	Determined with a Nisseisangyo Isotope Shift Zeeman Effect Atomic Absorption Spectrophotometer	0.0
Hg	Cold Vapor Flameless Atomic Absorption, Standard Methods, pp 121-130**	0.002
P†	Technicon II AutoAnalyzer, Industrial Method No. 155-71W (low range) Method No. 94-70W/B (high range)	 0.01 0.2
NH_4†	Technicon II AutoAnalyzer, Industrial Method No. 154-71W (low range) Method No. 98-70W/A (high range)	 0.01 0.2
Total sulfur	LECO combustion method, application No. 103	

Note: TKN = Total Kjeldahl Nitrogen.
* Determined with a Perkin-Elmer Heated Graphite Atomizer Absorption Unit to reach (all in $\mu g\ g^{-1}$) 0.0001 Cd, 0.004 Zn, 0.001 Cu, 0.0005 Fe, Mn, Pb, 0.0003 Ni, and 0.001 Cr.
** American Public Health Association (1976).
† Technicon Industrial Systems, Tarrytown, N. Y.

flask (without filtering) and diluted to volume with RO water. Then the digestion nitrogen was determined by the methods indicated in Table 1.

35. Nitric acid digestion. The nitric acid (reagent grade, ACS certified) digestion was accomplished by the procedures of Lee et al. (1978).

Chemical analysis of sediments

36. Samples of each sediment (before plant growth) under both flooded and upland conditions were extracted with DTPA according to the procedure of Lee, Sturgis, and Landin (1976) to determine available zinc, cadmium, copper, arsenic, mercury, iron, manganese, nickel, chromium, lead, and phosphorus. A total acid (nitric) digest was performed on all upland sediments (saltwater and fresh water), and the resulting solution was analyzed for total zinc, cadmium, copper, arsenic, iron, manganese, nickel, chromium, lead, and phosphorus. In addition, a TKN digest was used to determine sediment ammonia content.

37. DTPA-IW original, reduced sediment extraction. Wet sediment samples equivalent to 50 g oven dry weight (ODW) were weighed into a 500-ml polycarbonate centrifuge bottle and centrifuged at 4°C and 13,701 × g (9000 rpm) for 30 min. The volume of the resulting supernatant liquid (IW) was measured and then divided into two portions. One portion for metal and P analysis (40 ml) was preserved with four drops of ultrapure nitric acid; the other portion was preserved for ammonium analysis with four drops of concentrated sulfuric acid. Two hundred fifty millilitres of a 0.005 M DTPA + 0.01 M calcium chloride ($CaCl_2$) + 0.1 M triethanolamine (TEA) solution (Lee, Sturgis, and Landin 1978) buffered at pH 7.3 was added to the sediment remaining in the centrifuge bottle. The bottle was sealed and placed on a shaker for 24 hr. After 24 hr, the bottles were then centrifuged as before. The volume of the resulting supernatant liquid was measured; the supernatant was poured into a polyethylene bottle; and the liquid was stored at 4°C until time of chemical analysis.

38. Interstitial water (IW - reconstituted) samples. The metals

that were determined on the IW samples were the same as those in the acid digest and DTPA extraction, plus ammonium. Saltwater IW samples were also analyzed for sodium and potassium. In addition, pH and salinity were determined on saltwater sediment IW. A reconstituted IW sample was prepared with the air-dried upland sediments to determine drying effects on metal solubility in the IW. The procedure (as in the DTPA-IW extraction above) involved adding an amount of RO water to the air-dried sediment equal to the amount of initial IW contained in the original reduced sediment (sediment weight was calculated on an CDW basis). The centrifuge bottles were then shaken for 24 hr. Extraction of IW was accomplished as with the DTPA-IW (original reduced sediment) extraction procedure above.

39. TKN. The TKN procedure was the same for sediment samples as for plant material except that 1.0 g of sediment and 10 ml RO water were placed into the 100-ml Kjeldahl flask.

40. Nitric acid digest. The nitric acid digestion was accomplished by the following procedure. One gram of oven-dried sediment was placed into a 100-ml micro-Kjeldahl flask. Fifteen millilitres of concentrated nitric acid was added; the mixture was placed on a digestion rack; and the mixture was heated until almost dryness. Five millilitres of red fuming nitric acid was added and then the solution was again heated to almost dryness. The mixture was allowed to cool to room temperature and diluted with 30 ml 1.2 M hydrochloric acid (HCl). The solution was quantitatively transferred with 1.2 M HCl and filtered through Whatman No. 42 filter paper in a long-stem funnel into a 50-ml volumetric flask. The filter paper was rinsed three times with 5-ml portions of 1.2 M HCl. The filtered solution was diluted to volume with 1.2 M HCl.

41. Upland sediment pH. Ten grams of sediment (ODW basis) was weighed into 50-ml pyrex glass beakers. Twenty millilitres of RO water was added, and the mixture was stirred with a polyethylene rod until all dry particles had become wet. The suspension was stirred for 1 min every 15 min for 1 hr. After 1 hr, a small magnetic stirring bar was placed into the beaker and the suspension stirred at low speed with a

magnetic stirrer. During stirring, pH of the suspension was determined using a glass and reference calomel electrode on an Orion Model No. 800 digital pH meter (Orion Research Incorporated, Cambridge, Mass.).

42. Flooded sediment pH. To obtain the pH of the original reduced sediment, the pH of the IW original reduced sediment (obtained from the DTPA-IW original reduced sediment extraction procedure) was determined with a pH meter using a glass and reference electrode as discussed above.

43. Organic matter. Organic matter (OM) was determined by weight loss on ignition at 550°C. The procedure was a modification of that found in Standard Methods (American Public Health Association 1976) and was as follows. Approximately 5 g of sediment (ODW basis) was weighed to the nearest 0.1 mg and combusted at 550°C for 24 hr in a muffle furnace. The sample was allowed to cool to room temperature and weighed to the nearest 0.1 mg until constant weight. Weight loss on ignition was calculated and reported as percent organic matter (% OM).

44. Calcium carbonate equivalent. Calcium carbonate equivalent was determined on oven-dried sediments using gravimetric method No. 91-5 (Allison and Moodie 1965).

45. Total sulfur. Total sulfur (S) was determined on oven-dried sediments using the LECO combustion method, Application No. 103 (Laboratory Equip. Corp., St. Joseph, Mich.).

46. Oil and grease (O&G). The O&G content of the sediments was determined by the method given in the Chemistry Laboratory Manual (Federal Water Quality Administration 1969).

Physical analysis

47. Particle-size distribution. Particle size was determined on air-dried sediments using the method of Day (1956) as modified by Patrick (1958).

48. Moisture content. Moisture content of the sediments at three suction pressures (1/3, 1, and 15 bars; 1 bar = $10^5 Nm^{-2}$) was determined using gas pressure extractors and the manufacturer's operating procedure (Soil Moisture Equipment Company, Santa Barbara, Calif.).

Data analysis

49. Analysis of variance. An analysis of variance (ANOVA) using a randomized complete block experimental design was performed on the data to test for overall differences in heavy metal concentration, uptake, etc., between flooded and upland disposal conditions. In order to determine specific differences, the least significant difference (LSD) ($P = 0.05$) procedure (Steel and Torrie 1960) was used.

50. The coefficient of variation (CV) reported is the average of the site-specific coefficients of variation (Steel and Torrie 1960). The CV was used to indicate variability of the data. The CV is a relative measure of variation and is independent of the units used (Steel and Torrie 1960).

51. Multiple regression. The first step in developing the multiple regression analysis was a preselection of predictor variables. This was accomplished by performing a simple one-to-one correlation analysis of the data set. The freshwater and saltwater data were treated as two independent experiments.

52. A stepwise multiple regression analysis procedure using maximum R^2 improvement criteria was used to develop the prediction equations. The procedure was developed by the Statistical Analysis Systems (SAS) Institute (Barr et al. 1976). This technique does not use only a single model; instead, it looks for the "best" one-variable model, the "best" two-variable model, and so forth, of the input variables. It first finds the one-variable model producing the highest R^2 statistic. Then the next variable that would yield the greatest increase in R^2 is added. Once this two-variable model is obtained, each of the variables in the model is compared to each variable not in the model. For each comparison, the procedure determines if removing the variable in the model and replacing it with the presently excluded variable would increase R^2. After all possible comparisons have been made, the replacement that produces the largest increase in R^2 is made. Comparisons are made again, and the process continues until the procedure finds that no other replacement could increase R^2. The two-variable model thus obtained

is considered the "best" two-variable model for the given data set. The technique then adds a third variable to the model, according to the criteria used in adding the second variable. The comparison-and-replacement process is repeated, the "best" three-variable model is obtained, and so forth.

53. There were seven main groups of variables that were used in the multiple regression analysis. The seven were: DTPA extractable heavy metals of the original flooded sediment; DTPA extractable heavy metals from reconstituted air-dried sediment; initial interstitial water from original flooded sediment; initial interstitial water from reconstituted air-dried sediment; total heavy metal contents; sediment physical and chemical parameters; and plant parameters.

PART III: RESULTS AND DISCUSSION

Freshwater Experiment

Sediment physical characteristics

54. Moisture content. The moisture content of the freshwater sediments at three tensions (soil suctions) is presented in Table 2. A moisture content between 1/3 and 15 bars is an indication of plant available moisture. The more sandy-to-sandy loam sediments had less plant available moisture than did the loam-to-silt loam sediments.

55. Particle-size distribution. Particle-size distribution (texture) is listed in Table 2 for the sediments used in the freshwater portion of the study. The texture of the sediments was predominately silt loam. Several of the sediments were loam and sandy loam, and only one was sand.

56. The silt and clay size (fine) fraction of a sediment is important because of its adsorption capacity for cations such as heavy metals. Stoffers et al. (1977) found that the greatest concentration of heavy metals was in the clay size fraction of sediment. Schell and Nevissi (1977) also determined that enriched levels of heavy metals were associated with the fine size fraction of sediments. Hallberg (1974) found that the heavy metals found in sediments from an area off the coast of Holland were closely associated with the fine size fraction.

57. Hydrous oxides of mainly iron and manganese are another major component of the fine fraction of a sediment and have an adsorption capacity for heavy metals. Hydrous oxides of iron, manganese, and aluminum have been shown to be closely associated with the fine size fraction of sediments. Gong, Rose, and Suhr (1977) showed that adsorption of heavy metals onto oxides of iron and manganese resulted in heavy metal enrichment in sediment. McNeal and Rose (1974) suggested iron and manganese oxides were involved in adsorption of heavy metals.

58. The fine size fraction of a sediment is closely associated with the abundance and chemistry of heavy metals in sediment; hence, it is very important.

Table 2

Selected Physical Characteristics of the Freshwater Sediments Used in the Study

Location*/	Moisture Content, %			Plant Available	Particle Size, %			
Site	1/3 Bar	1 Bar	15 Bar	Moisture, %	Sand	Silt	Clay	Texture**
DE 1	60.2	44.7	19.6	40.6	33.8	53.8	12.4	Silt loam
2	45.2	31.4	12.0	33.2	15.8	65.8	18.4	Silt loam
3	19.6	15.7	10.5	9.1	39.6	32.9	27.5	Clay loam
MC 1	27.7	19.5	9.5	18.2	43.4	44.1	12.5	Loam
2	44.2	32.3	13.0	31.2	27.1	62.0	10.9	Silt loam
3	29.7	20.0	4.6	25.1	47.5	42.9	9.6	Loam
IN 1	15.5	10.4	6.0	9.5	73.3	20.0	6.7	Sandy loam
2	30.0	22.7	10.2	19.8	36.7	58.3	5.0	Silt loam
3	27.6	26.8	18.5	9.1	38.8	46.6	14.6	Loam
MW 1	39.6	33.2	19.6	20.0	9.6	65.4	25.0	Silt loam
2	52.8	33.7	20.3	32.5	3.4	70.7	25.9	Silt loam
3	43.0	33.5	15.6	27.4	16.3	62.4	21.3	Silt loam
ME 1	20.6	7.3	4.6	16.0	91.4	5.7	2.9	Sand
2	56.3	30.7	29.5	26.8	75.8	16.2	8.0	Sandy loam
3	83.6	42.8	29.4	54.2	16.3	58.7	25.0	Silt loam
CV†	2.1	1.8	10.6	8.4	6.2	4.5	6.5	

* Abbreviations correspond to those listed in Figures 5-7.
** Based on U. S. Department of Agriculture 7th Approximation Classification Scheme.
† CV = coefficient of variation (%).

Sediment chemical characteristics

59. Some of the general chemical characteristics of the freshwater sediments are given in Table 3.

60. Organic matter. Organic matter in the freshwater sediments ranged from a low of 2.77 percent (ME 1) to as high as 29.5 percent (ME 3). Most values were between 5 and 15 percent.

61. Organic matter has been shown to be involved in heavy metal mobility and plant availability in sediment. Krom and Sholkovity (1978) found that all of the iron in several anoxic marine sediment interstitial water was organically bound, while manganese was present mainly as labile inorganic complexes. Bloomfield and Sanders (1977) indicated that copper availability (as measured in water extracts) increased due to complexation of copper by humified organic matter. Organic matter with its heavy metal complexation and/or adsorption characteristics was shown to be the primary cause of cadmium enrichment in the sedimentary environment (Gong, Rose, and Suhr 1977). Organic matter has been correlated with plant available manganese and extractable soil manganese (Randall, Schulte, and Corey 1976). Other heavy metals such as copper, nickel, cobalt, and zinc also have been shown to be associated with organic matter (Nissenbaum and Swaine 1976). Cleveland and Rees (1976) also indicated that solubilization of heavy metals is increased by complex formation or colloid peptization due to humus contained in the organic matter of a soil. Soil organic matter has been postulated by Zunino and Martin (1977) to constitute the most important pool of micronutrients (heavy metals) available to plants and other biological systems. The large quantities of organic matter in the freshwater sediments should therefore play a significant role in the heavy metal mobility and biological availability of the sediments.

62. Calcium carbonate - sediment pH. Calcium carbonate equivalent (CCE) for the 15 freshwater sediments ranged from near 6 to more than 50 percent (Table 3). All sediments were considered to be calcareous. The pH of most of the sediments was alkaline (pH >7.00) under both flooded and upland conditions.

63. Calcium carbonate and pH are intimately related. As soil pH increases, the availability to plants of some of the heavy metals (in

Table 3

Selected Chemical Parameters of the Freshwater Sediments

Location*/ Site	Organic Matter %	$CaCO_3$ Equivalent %	pH Flooded**	pH Upland†	Total P mg g^{-1}	TKN mg g^{-1}	Oil and Grease mg g^{-1}	Total S mg g^{-1}
DE 1	10.7	32.1	7.5	8.5	1.11	0.68	7.8	1.7
2	10.7	23.2	7.5	7.6	2.38	2.32	9.2	1.9
3	3.1	22.3	7.3	8.1	0.44	0.68	0.2	3.5
MC 1	5.7	19.5	ND††	7.4	0.70	1.01	0.5	1.6
2	14.2	13.5	7.2	7.1	2.56	3.77	5.8	4.1
3	13.0	21.1	7.1	7.2	2.11	3.74	4.6	3.8
IN 1	6.6	18.2	7.4	7.3	0.74	0.94	4.4	1.6
2	7.3	13.6	7.4	7.6	0.73	0.63	12.2	6.0
3	21.9	16.7	7.5	6.7	5.60	3.50	6.8	7.2
MW 1	13.1	34.5	7.4	7.6	1.55	2.93	4.8	2.1
2	8.8	51.7	7.2	7.7	0.49	3.07	0.2	3.7
3	8.8	56.3	7.4	7.7	0.55	6.33	0.2	1.3
ME 1	2.7	7.6	7.3	7.0	0.22	0.47	0.2	0.3
2	27.3	6.5	7.5	6.4	0.39	2.08	1.5	2.0
3	29.5	35.4	7.3	7.0	1.34	2.79	2.2	2.3
CV‡	5.9	4.5	0.8	0.4	2.10	4.80	5.4	2.7

* Abbreviations correspond to those listed in Figures 5-7.
** Flooded pH is pH of the initial interstitial water.
† Upland pH is pH of a 1:2 sediment to solution suspension using air-dried sediment.
†† ND = not determined.
‡ CV = coefficient of variation (%).

particular, zinc) has been shown to decrease (Saeed and Fox 1977; Singh and Sekhon 1977; Udo, Bohn, and Tucker 1970; MacIntosh et al. 1978).

64. Saeed and Fox (1977) investigated relations between pH and zinc solubility in acid and calcareous soils. They observed an inverse linear relationship between pH and zinc solubility in acid soils. On two soils, however, an increase was noted in the amounts of zinc in solutions above pH 7.0. They explained that this increase in zinc solubility above pH 7.0 was due to dispersion of organic matter that either released complexed zinc or provided chelating agents for added zinc and reduced absorption or precipitation. In an alkaline medium, zinc can change from a cation to an anion to form a zincate ($Zn(OH_4)^+$). In the presence of excess calcium, such as in a calcareous sediment, zinc uptake could be significantly enhanced. Saeed and Fox (1977) have stated that overliming of acid soils, or high calcium carbonate in soils, have frequently resulted in significant zinc uptake, most probably due to the dispersion of organic matter as previously discussed.

65. Singh and Sekhon (1977) also implicated calcium carbonate and pH (and organic matter) in zinc deficiencies in plants grown under alkaline soil conditions and found that zinc availability was controlled by adsorption-desorption phenomena. They found that the retaining powers of clay and organic matter were predominately due to their cation exchange capacities. In addition, they showed that the clay functioned independently, but that calcium carbonate and organic matter interacted for adsorption of zinc. Udo, Bohn, and Tucker (1970) determined that carbonate and organic matter contents of soils were ultimately involved in controlling zinc availability in calcareous soils. MacIntosh et al. (1978) also found that zinc in sediments was bound mainly as carbonate.

66. While most of the heavy metal work on calcareous soils has been associated with zinc, recent research has shown calcium carbonate content and pH to have similar interactions with some of the other heavy metals. Sinha et al. (1978) investigated solubility relationships of iron, manganese, copper, and zinc in alkaline and calcareous soils. They found that soils that undergo alternate cycles of reversible oxidation-reduction processes were found to maintain higher solubilities

of iron and manganese than other soils.

67. Lead availability has been shown by Zimdahl and Skogerboe (1977) to be dependent on calcium carbonate, organic matter, and hydrous oxides.

68. Calcium carbonate and pH have been implicated in controlling solubility and plant uptake of manganese. When organic matter (Randall, Schulte, and Corey 1976) and pH (Browman, Chesters, and Pionke 1969) were included in regression analyses in the prediction of plant available manganese, the regression equation was significantly improved. Khan and Ryan (1978) also found improved prediction of manganese uptake when calcium carbonate and pH were included in multiple regression analyses.

69. The significance of the discussion on calcium carbonate and pH is that heavy metal availability to plants from a sediment containing high levels of zinc, copper, and possibly lead may not necessarily be disregarded because the sediment is calcareous and has a pH greater than 7.0. Significant plant uptake of these heavy metals from a calcareous sediment can occur if the organic matter content of the sediment is high. Dispersion of the organic matter can occur, and, with an alkaline pH, anionic forms of some of the metals (especially zinc, i.e. $Zn(OH_4)^+$) can form that are readily plant available.

70. Total sulfur. The total content of the sediments ranged from a low of 0.3 mg g^{-1} to as high as 7.2 mg g^{-1} (Table 3). These values are somewhat lower than those normally found in most agricultural soils. Total sulfur contents of 64 to 700 mg g^{-1} have been reported by a number of researchers. McLachlan and DeMarco (1975) investigated soil sulfur fractionations of several soils from New South Wales, Australia, that ranged in total sulfur content from 64 to 207 mg g^{-1}. McLaren and Swift (1977) used soils from several areas in England that ranged in total sulfur content from about 250 to near 700 mg g^{-1}. Nor and Tabatabai (1977) used soils that represented the major soil types in Iowa that ranged in total sulfur content from 151 to 642 mg g^{-1}. Tabatabai and Bremner (1970) found that the total sulfur content of several soils (0- to 15-cm depth) in Iowa ranged from 75 to 338 mg g^{-1}.

71. The sulfur in a sediment can influence heavy metal

availability to plants. Fleming and Alexander (1961), in an investigation of acidity in South Carolina tidal marsh soils, found that the acidity problem was due to sulfur. It was similar to the problem called Katteklei in soils in Holland. Fleming and Alexander (1961) concluded that the sulfur acidity mechanism in tidal marshes was sulfate from seawater being reduced to sulfides. Upon undergoing air drying, the sulfides were oxidized to sulfates by chemical and biological reactions. If there were not enough alkaline earth carbonates present to neutralize the sulfuric acid produced, high acidity resulted. Fleming and Alexander (1961) indicated that total sulfur content and determination of pH on soil samples before and after drying were indicative of the sulfur acidity problem.

72. The heavy metal association with sulfur, primarily as sulfides, had been reported by several workers. Engler and Patrick (1973) investigated sulfate reduction and sulfide oxidation in flooded soils and found that iron and manganese oxides in several of their mineral forms were directly involved in the sulfate reduction processes. Framson and Leckle (1978) found that cadmium precipitated primarily through surface exchange reactions with ferrous monosulfide substrates and as essentially unsubstituted cadmium sulfide. Sommers, Tabatabai, and Nelson (1977) stated that the forms and amounts of sulfur may influence the solubility and behavior of metals in sewage sludge.

73. The sulfur in sediment can affect the plant availability of many of the heavy metals. If the sediment is chemically reducing, heavy metals bound as sulfides will be less mobile (Gambrell, Khalid, and Patrick 1978). However, upon oxidation of the sediment, the sulfide bound heavy metals are released when sulfide is oxidized to sulfate (Gambrell, Khalid, and Patrick 1978; Framson and Leckle 1978). Gambrell, Khalid, and Patrick (1978) have indicated that mobilization of heavy metals upon oxidation of sulfides may not always occur. If appreciable quantities of iron and manganese oxides are present, the heavy metals released from sulfide forms may be reimmobilized by reaction and precipitation with iron and manganese. Hence, it is important to know the sulfur

status of a sediment because of potential mobilization and plant uptake of heavy metals.

74. Oil and grease. The O&G concentration of the sediments is also reported in Table 3. The O&G ranged from 0.2 mg g^{-1} to as high as 12.2 mg g^{-1}.

75. In a study on the evaluation of O&G contamination associated with dredged material containment areas, O&G concentration in sediments from around the country ranged from 0.15 to 32.0 mg g^{-1} and averaged 0.9 mg g^{-1} (Engineering-Science 1977). Engineering-Science (1977) found that O&G was not released to a significant extent from sediments as a result of dredging operations. Shelton and Hunter (1975) indicated that a significant portion of oil pollutants discharged into aquatic environments was incorporated into bottom sediments of receiving water. Sedimentation of O&G has been suggested to occur by the addition of clays (Shelton and Hunter 1974).

76. High O&G concentration in sediments is one of the most characteristic features of chronic oil contamination (Shelton and Hunter 1974). The high O&G concentration in the sediments is likely to remain undegraded because of the anaerobic nature of bottom sediments. The activity of the anaerobic bacteria responsible for the degradation of the O&G is limited either by toxic metabolic products and competition for essential nutrients or by toxic substances present in the O&G fraction. The O&G content of eight sediments used in the present study were an order of magnitude greater than that reported in the literature.

77. The particular significance of O&G can be summarized as: (a) their various degrees of biodegradability, which depend on molecular composition and structure, thus causing certain fractions to persist in the environment; (b) their toxicity--many low boiling aromatic hydrocarbons are essentially nontoxic to most forms of life; and (c) their being carcinogens - many aromatic hydrocarbons have been shown to cause cancer in test organisms (Shelton and Hunter 1975).

78. Total P and TKN. The range of total P was from a low of 0.22 mg g^{-1} to a high of 5.60 mg g^{-1} (Table 3). In general, the level of total P is not significantly different than that normally found in

soils or sediments. Jackson (1964) has stated that the P content of most mineral soils falls between 0.2 and 5.0 mg g^{-1}, which is almost the same range as found in this study.

79. Sediment TKN ranged from a low of 0.47 mg g^{-1} to a high of 6.33 mg g^{-1} (Table 3). These TKN values were not excessively high or low when compared to those normally found in soils or sediments. Most mineral soils have a TKN range of 0.2 to 2.5 mg g^{-1} (Jackson 1964). A more complete description of the complex chemistry of P and N in soils has been discussed by Jackson (1964).

80. Oxidation-reduction (redox) potential. The redox potential of the sediments under the two simulated disposal environments is presented in Figure 15. Redox potential was much higher for the upland sediments than for the flooded sediments. The redox potential of the flooded sediments was initially between -200 and -300 mV, depicting intensely reduced conditions, and remained near that for the duration of the experiment. The redox potential of the upland sediments was initially some 200 mV greater than that of the flooded sediments, decreased several hundred millivolts to near -200 mV upon initial watering, and then increased to near 300 mV for the remainder of the experiment. The frequent increases and decreases in the redox potential on the upland sediments closely followed the watering sequence of the upland sediments. Immediately after water applications, the redox potential decreased; then after a period of plant growth (i.e., water loss due to evapotranspiration), the redox potential increased.

81. Even with the frequent increases and decreases in the redox potential caused by watering, the overall average redox potential of the upland sediments was more oxidative than the intensely reduced flooded sediments. This difference could significantly affect plant uptake of heavy metals. Gambrell, Khalid, and Patrick (1978) have discussed the importance of redox status of a sediment with respect to potential heavy metal uptake. Oxidation-reduction conditions can be chemically or microbiologically produced. Chemically, oxidizing conditions are characterized by the presence of oxygen and other oxidized

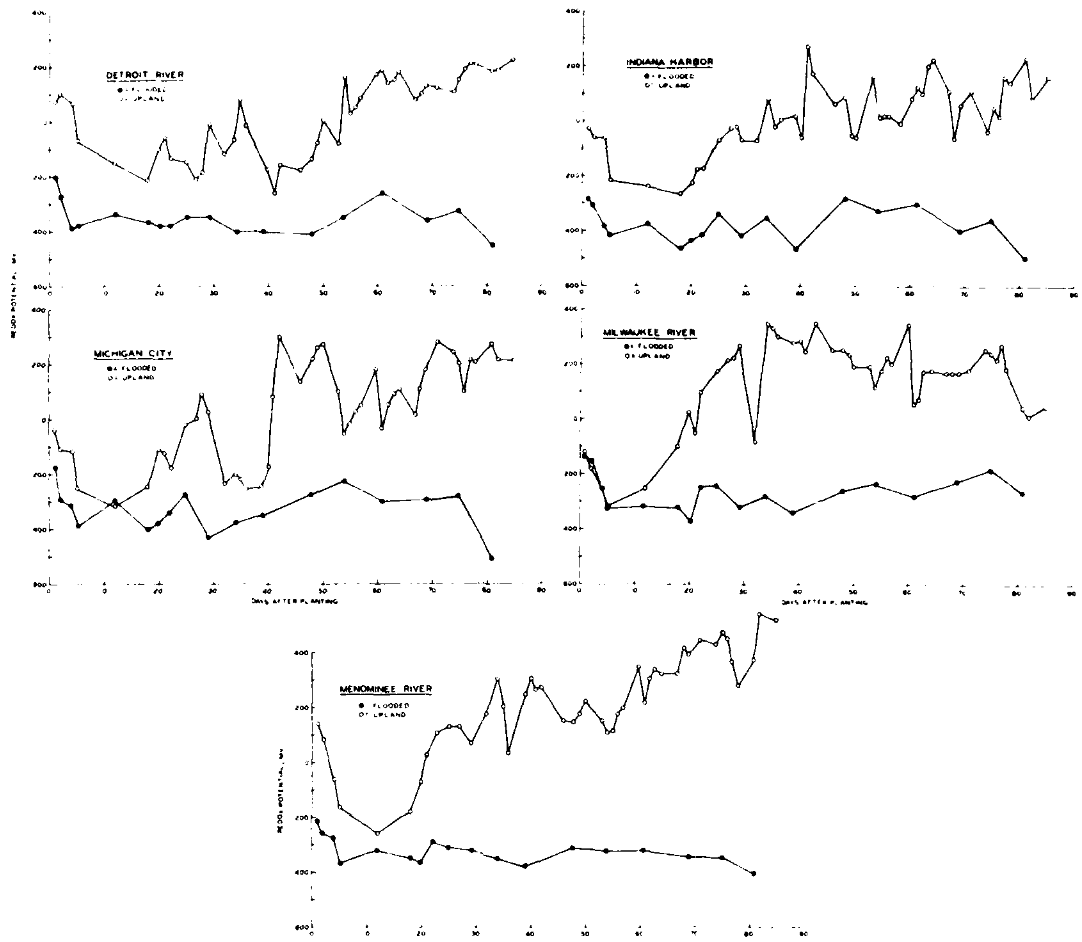


Figure 15. Redox potential versus time after planting of *C. esculentus* grown under flooded and upland disposal environments

components of the sediment such as nitrate, ferric iron, manganic manganese, sulfate, and carbon dioxide. Reduced conditions occur when oxygen and the other oxidized materials are absent and their reduced counterparts are present. These include ammonium, manganous manganese, ferrous iron, sulfide, and methane. Microbiological processes are responsible for conversion of most soil components from oxidized to reduced forms. The reduction reactions never take place as long as oxygen is present, but the absence of oxygen causes microorganisms to reduce the other oxidized components of the soil. When oxygen reenters the sediment, the reactions are reversed and the reduced forms are converted to oxidized

forms. Both chemical and microbial reactions are involved.

Plant growth

82. Flooded environment. Plant growth under the flooded environment is shown in Figures 16-20. Differences in growth occurred between geographic locations as well as between sites within each location. Flooded sediment from DE 2 supported the best plant growth of the DE sediments (Figure 16). Michigan City site 2 flooded sediment produced the most plant growth of the MC sediments (Figure 17). Flooded sediment from IN 3 produced the best plant growth on IN sediments (Figure 18). The most plant growth on flooded sediment from MW was obtained on MW 1 (Figure 19). Plant growth on flooded sediment from ME 1 and 2 appeared to be about the same and was much greater than plant growth on sediment from ME 3 (Figure 20). Very little plant growth occurred on flooded sediment from ME 3 (Figure 20).

83. Upland environment. Plant growth under the upland environment is also shown in Figures 16-20. As with the flooded environment, differences in growth occurred between geographic locations as well as between sites within each location. The same relative differences in growth on the flooded sediments were present for plant growth on the upland sediments. Plant growth on upland sediment from ME 3 was much greater than that on flooded sediment from ME 3.

Plant yield

84. Aboveground. Yield data for *C. esculentus* grown under flooded and upland environments are presented in Table 4. Yield has been separated into three components: live, dead, and the sum of live and dead. Comparison of the yield of live tissue between flooded and upland environments for each site reveals that the flooded environment yielded more than the upland environment at 6 of the 15 sites (DE 2, MC 1 and 2, IN 1 and 2, and MW 1). Total aboveground yield was also greater under the flooded environment than the upland environment for those same sites plus MC 3, IN 3, and MW 2.

85. Belowground. Belowground yield data (comprised of tubers and roots) are also presented in Table 4. Root tissue was not harvested from the upland environment because it was difficult to obtain whole

Table 4

Yield of the Freshwater Marsh Plant *C. esculentus* Grown Under

Reduced (Flooded) and Oxidized (Upland) Environments

Location*/	Aboveground Yield,** g pot^{-1}						Belowground Yield,** g pot^{-1}			
	Live		Dead		Total Aboveground		Tubers		Roots	
Site	Flooded	Upland	Flooded	Upland	Flooded	Upland	Flooded	Upland	Flooded	Upland
DE 1	5.9	7.6	1.5	1.6	7.4	9.2	9.1	12.7	5.9	--
2	215.6	47.5	15.6	5.1	231.1	52.7	192.8	70.2	83.2	--
3	5.6	7.9	0.7	0.9	6.3	8.7	7.5	12.3	2.8	--
MC 1	101.7	55.7	4.0	7.5	105.6	63.1	100.0	67.9	64.1	--
2	159.3	75.0	17.5	27.8	176.9	102.9	153.8	101.9	76.0	--
3	46.4	54.4	58.3	27.2	104.7	81.7	78.4	88.2	53.7	--
IN 1	37.9	7.6	1.7	1.1	39.7	8.7	49.0	10.2	30.1	--
2	79.1	26.8	4.6	3.8	83.7	30.6	95.4	40.5	38.0	--
3	31.9	20.6	84.0	4.4	115.9	25.0	11.1	32.7	17.4	--
MW 1	125.9	78.9	7.7	14.5	133.7	93.4	108.0	103.5	29.0	--
2	48.9	35.3	2.8	3.8	51.7	39.1	48.5	48.3	20.1	--
3	46.4	44.4	1.8	3.8	48.3	48.3	54.6	62.2	15.2	--
ME 1	16.8	35.1	19.0	2.7	35.8	37.8	22.1	55.4	29.9	--
2	8.9	21.9	14.5	2.2	23.4	24.1	4.2	42.9	6.9	--
3	1.5	27.2	1.5	10.2	3.0	37.4	1.8	33.1	0.8	--
†$LSD_{0.05}$	17.9		16.9		11.9		18.0		--	

* Abbreviations are the same as those listed in Figures 5-7.

** All yields are oven dry weights. To convert yield to g m^{-2}, multiply by 35.3.

† $LSD_{0.05}$ = Lease Significant Difference at α = 0.05.

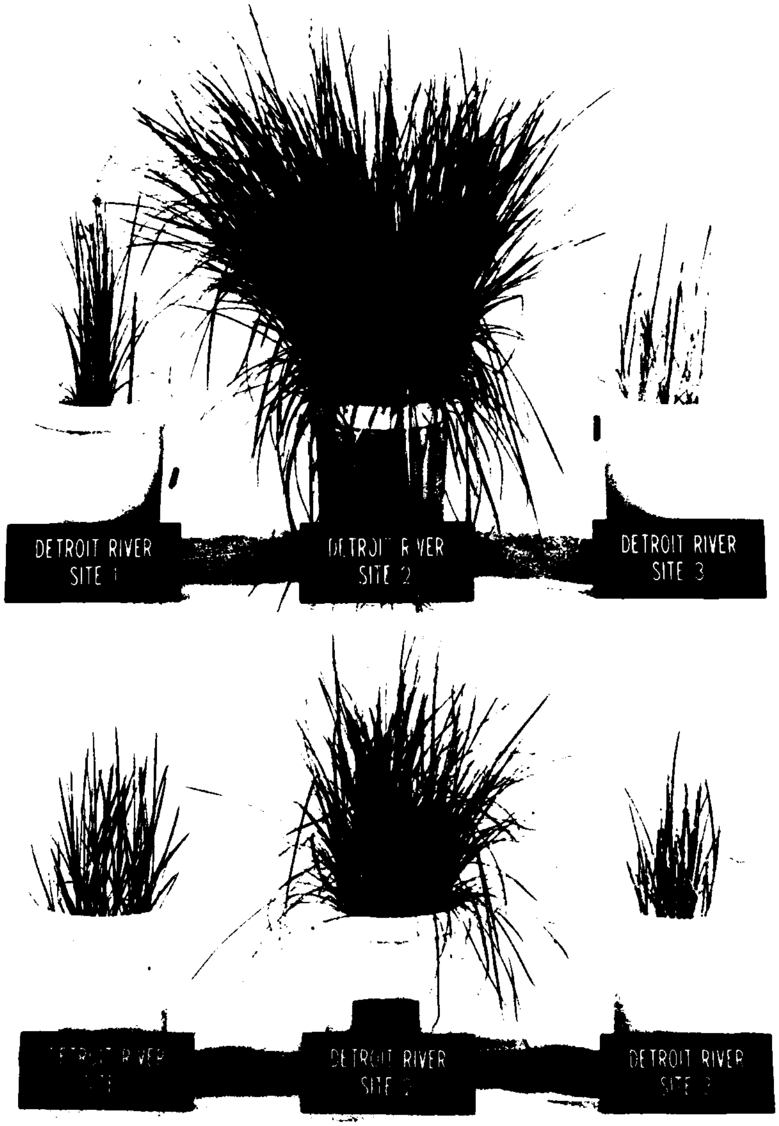


Figure 16. Growth of *C. esculentus* under flooded and upland disposal conditions on sediments from three sites in the Detroit River (DE), Mich.

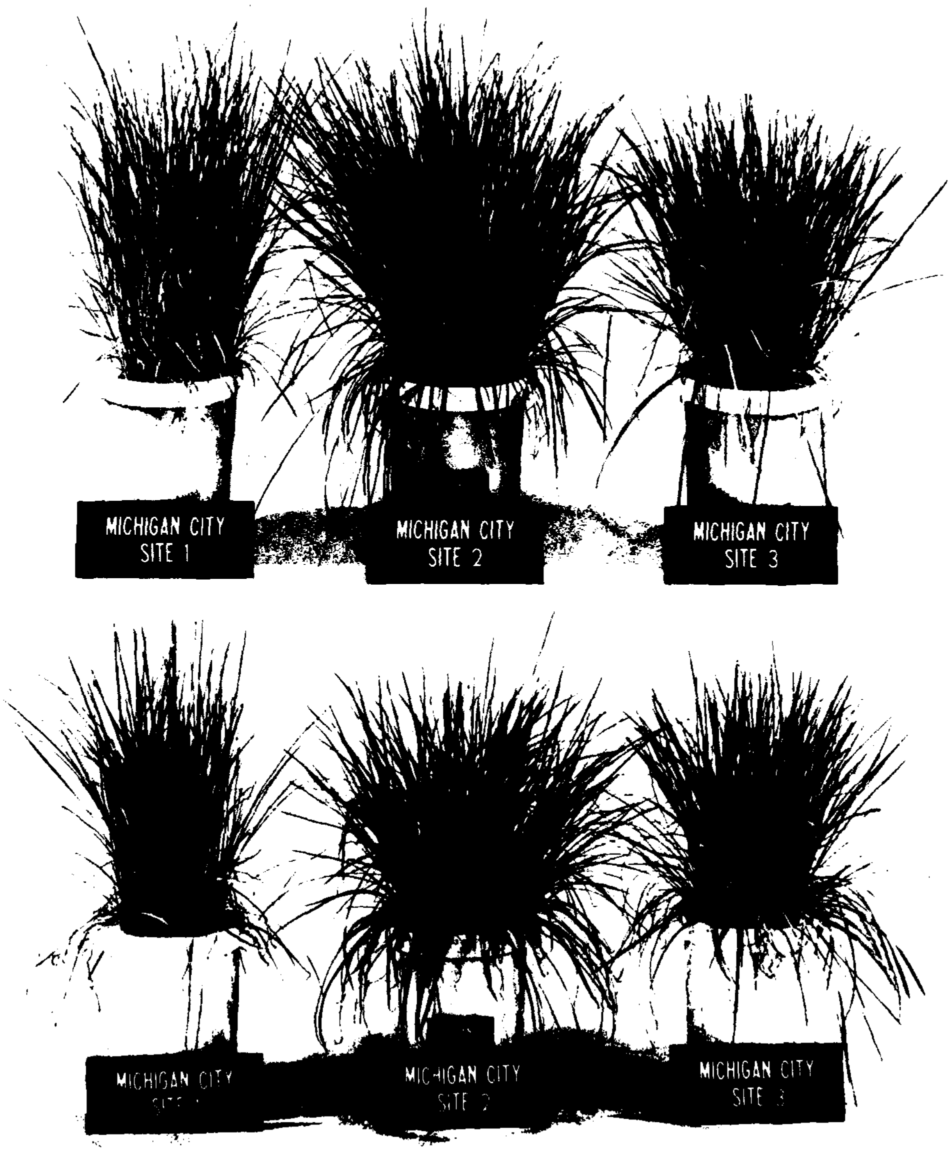


Figure 17. Growth of *C. esculentus* under flooded and upland disposal conditions on sediments from three sites in Michigan City Harbor (MC), Ind.

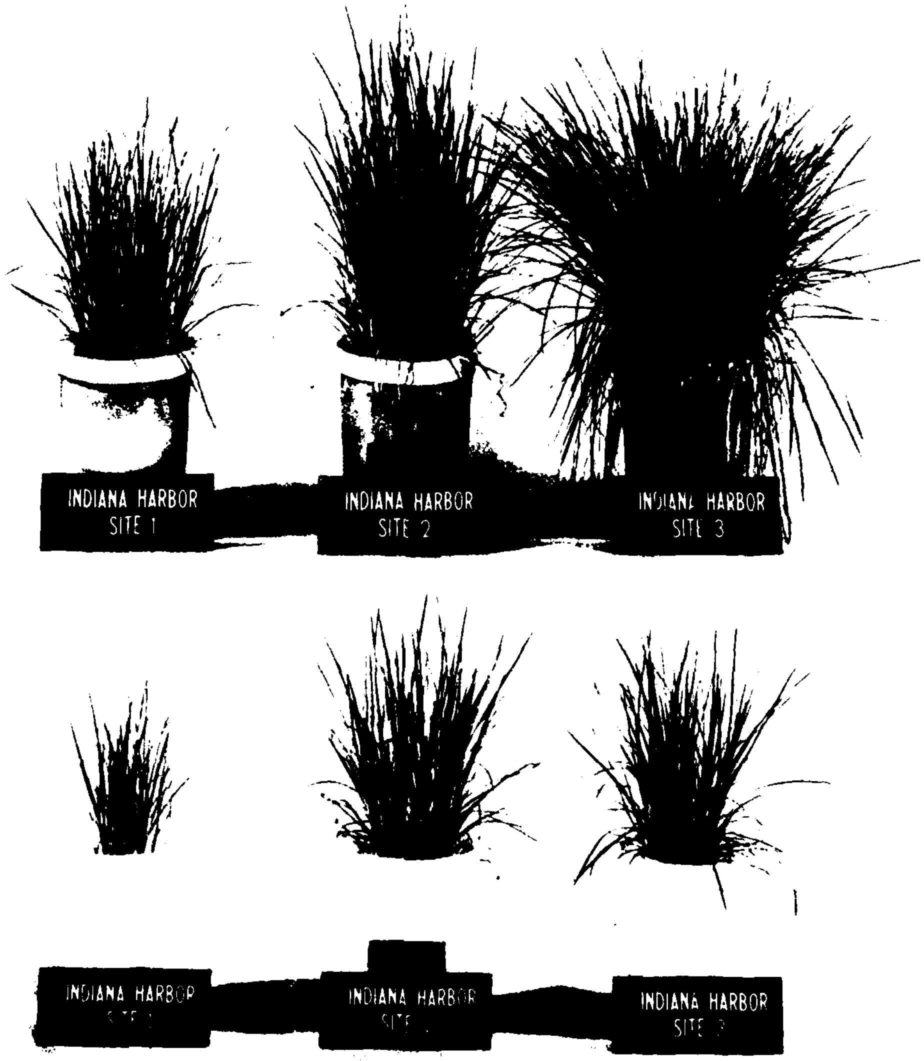


Figure 18. Growth of *C. esculentus* under flooded and upland disposal conditions on sediments from three sites in Indiana Harbor (IN), Ind.

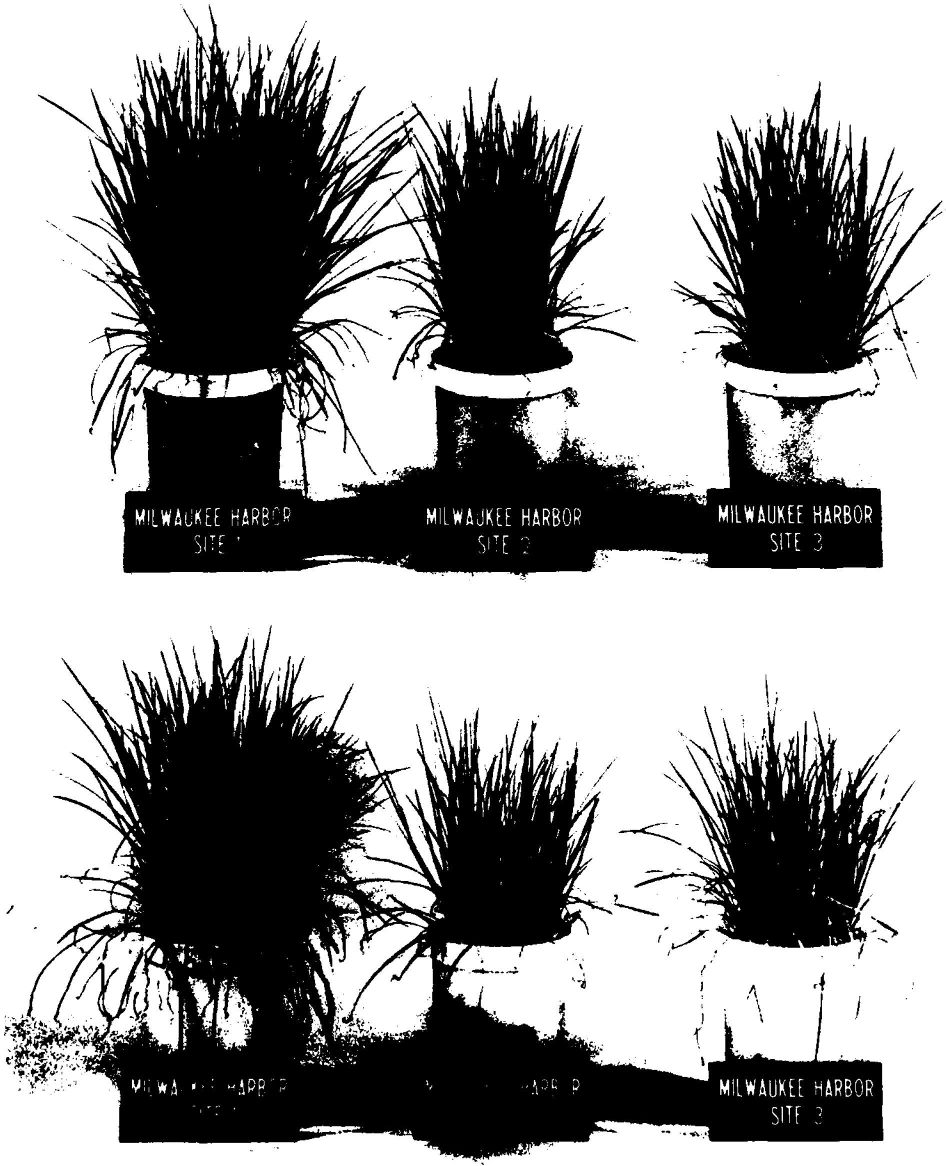


Figure 19. Growth of *C. esculentus* under flooded and upland disposal conditions on sediments from three sites in Milwaukee Harbor (MW), Wis.

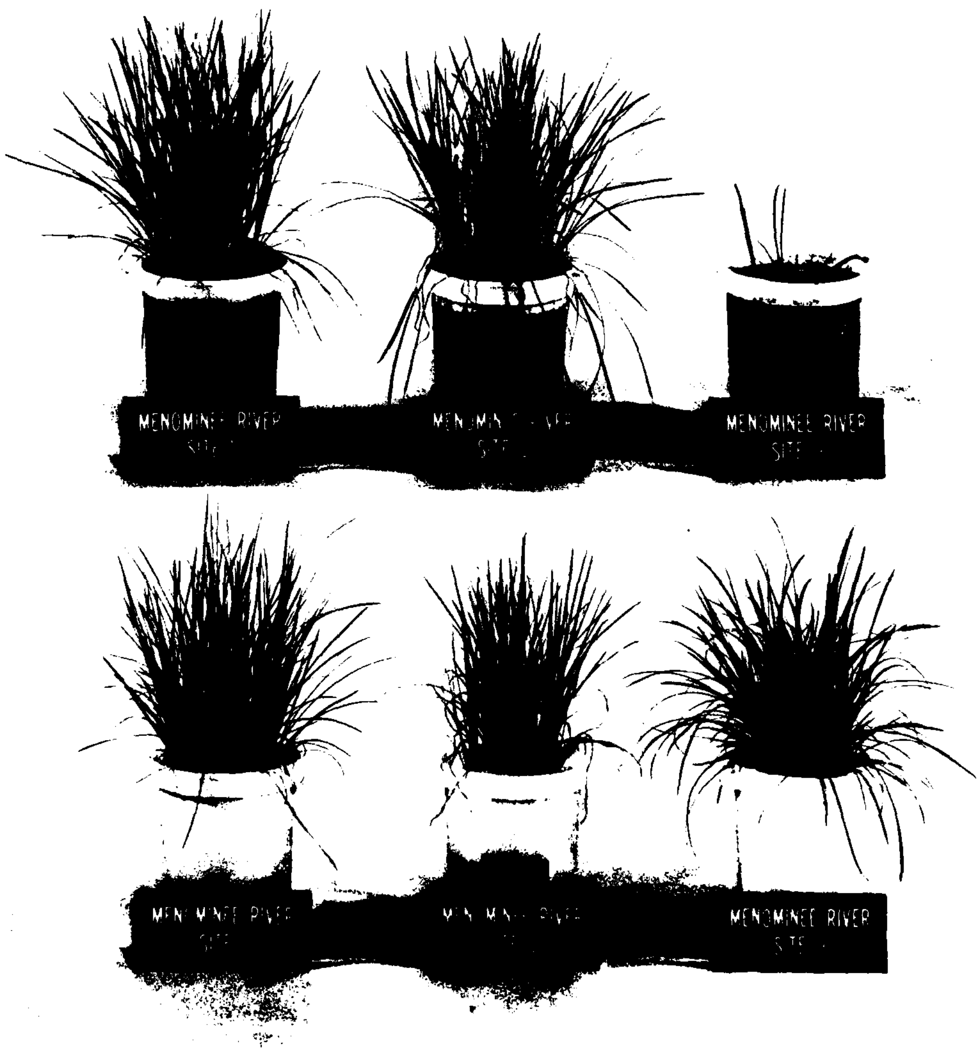


Figure 20. Growth of *C. esculentus* under flooded and upland disposal conditions on sediments from three sites in the Menominee River (ME), Wis.

roots as the root tissue was very fragile. Therefore, no comparison of root yield between flooded and upland environments could be made.

86. Yield of tubers was greater under flooded environments compared to upland environments at only 5 of the 15 sites (DE 2, MC 1 and 2, and IN 1 and 2).

87. Barko and Smart (1979) have shown that differences in growth and yield of *C. esculentus* grown on the flooded sediments were related to sediment fertility. They demonstrated that all plants grown on the flooded sediments were nitrogen limited, the exception being plants grown on sediment from DE 1, which was phosphorus limited. Barko and Smart (1979) attributed the tendency toward relatively increased belowground biomass production to nitrogen and phosphorus limitation.

88. If the sum of total aboveground yield and tuber yield was considered, 9 out of 15 sites had greater yield from flooded sediments compared to upland sediments; 4 out of 15 sites had equal yields from both sediments; and only 1 site had greater yield from upland sediments (ME 3). This behavior was consistent with data in the literature for growth of semiaquatic plants such as lowland rice (*Oryza sativa* L.). Patrick and Fontenot (1976) showed that vegetative growth of rice was greater under reduced conditions than under oxidized conditions and attributed the better growth to solubilization of phosphorus due to the reducing conditions caused by submergence. Hossner, Freeouf, and Folsom (1973) showed that maximum rice yields were obtained when soil solution P was greater than 0.1 $\mu g\ g^{-1}$. Upland crops required higher soil solution P concentrations to obtain maximum yields (Asher and Loneragon 1967; Ozanne and Shaw 1968; Fox and Kamprath 1970).

89. Another explanation for the greater yield having occurred on the flooded sediments could have been that of decreased nitrogen content of the upland sediments compared to the nitrogen content of the flooded sediment.

90. Under alkaline (pH <7.0) conditions, alternate flooding and drying causes nitrogen loss through nitrification during the drying cycle, followed by denitrification during the flooded cycle (Patrick and Wyatt 1964; Reddy and Patrick 1977a) plus the added loss of nitrogen

by ammonia volatilization (DeLaune and Patrick 1970). Under acid conditions (pH <7.0), nitrogen losses can occur by the same mechanism except for ammonia volatilization (Patrick and Wyatt 1964; Patrick and Reddy 1976). Upland sediments did have alternate wet-dry periods (Figure 15), which could explain the decreased yield of plants grown on the upland sediments. Since the upland sediments did have periods of relatively reduced conditions, ammonia volatilization could have occurred during the drying period after water addition to plants on the upland sediments. The combination of reduced nitrogen content and reduced phosphorus availability to the plants grown on the upland sediments could result in substantially lower yields on sediments placed in an upland environment.

Total heavy metal content

91. The freshwater sediments were selected because of their reported high concentrations of total heavy metals. The total heavy metal contents of the freshwater sediments are given in Table 5. The total heavy metal content of the freshwater sediments was within the range of other reported contaminated sediments. There were exceptions, however, and these are discussed in the sections below under the appropriate heavy metal.

92. Zinc. The total zinc content of the freshwater sediments was not location specific, but rather site specific. The range in total zinc content of the sediments was very wide, 124 to 31458 $\mu g\ g^{-1}$. The range in zinc concentrations of the sediments was within that found in the literature for contaminated freshwater sediments (Table 6), except for the extremely high concentration for MW 2 of 31458 $\mu g\ g^{-1}$.

93. Cadmium. The total cadmium concentration of the freshwater sediments ranged from 0.1 to 45.6 $\mu g\ g^{-1}$ and averaged 16.5 $\mu g\ g^{-1}$. Total cadmium concentration of the sediments was site specific rather than location specific. The total cadmium concentration was within the range of cadmium contents reportedly found in contaminated sediments (Table 7).

94. Copper. Total copper concentration in the sediments ranged from 10 to 341 $\mu g\ g^{-1}$ and averaged 87 $\mu g\ g^{-1}$. The total copper

Table 5

Concentration of Heavy Metals in Nitric Acid Digests of Freshwater Sediments

Location*/	Concentration, $\mu g\ g^{-1}$									
Site	Zn	Cd	Cu	Fe**	Mn	As	Hg	Ni	Cr	Pb
DE 1	2423	29.5	198.9	74.31	1203	11.4	0.36	62.5	94.8	226
2	2048	21 5	202.6	56.97	536	7.5	0.56	152.8	327.5	326
3	233	7.7	21.6	17.10	401	3.3	0.13	IS†	IS	IS
MC 1	796	6.2	21.2	11.56	258	2.5	0.06	20.0	9.5	30
2	1857	39.8	115.0	19.73	518	4.7	1.02	IS	IS	IS
3	978	35.9	121.4	29.81	523	2.3	0.18	105.2	135.5	656
IN 1	660	7.6	35.3	40.17	638	18.8	0.08	22.0	96.3	99
2	1433	16.0	64.8	89.81	1461	27.0	0.29	37.3	117.3	214
3	8867	45.6	340.6	291.31	2503	37.5	1.50	107.2	1974.3	1521
MW 1	921	14.8	82.3	23.91	541	7.9	0.60	48.7	231.3	385
2	31458	7.8	15.8	12.67	523	1.1	0.01	19.4	23.5	25
3	711	5.8	12.0	9.86	469	0.0	<0.009	14.2	10.0	26
ME 1	124	0.1	10.5	7.02	164	4.1	0.05	8.2	10.5	143
2	3992	0.1	24.0	8.56	267	6.4	0.27	10.5	8.2	315
3	230	9.3	37.5	27.41	1213	316.5	0.44	19.9	23.7	60
CV††	61	25.6	17.0	6.90	10	26.0	77.00	11.3	53.4	40

* Abbreviations are the same as those listed in Figures 5-7.
** Concentration of Fe is in milligrams per gram.
† IS = Insufficient sample for analysis.
†† CV = Coefficient of variation, %.

Table 6

Total Zinc Content of Some Freshwater Sediments

Concentration or Range $\mu g\ g^{-1}$	Literature Reference
11.3	Khalid, Gambrell, and Patrick (1976)
25-190	U. S. Environmental Protection Agency (1975a)
29-123	Mudroch and Capobianco (1978)
90-8790	McIntosh et al. (1978)
100-190	Williams et al. (1978)
142-320	Skei and Paus (1979)
314-368	Nriagu et al. (1979)
360-2710	U. S. Environmental Protection Agency (1975b)
625-10580	U. S. Environmental Protection Agency (1977)
1035	Harding and Whitton (1978)

Table 7

Total Cadmium Content of Some Freshwater Sediments

Concentration or Range $\mu g\ g^{-1}$	Literature Reference
1.0-1.9	Mudroch and Capobianco (1978)
1.0-9.8	Suzuki et al. (1979)
1-851	McIntosh et al. (1978)
<2-9	U. S. Environmental Protection Agency (1975a)
3.4-6.6	Nriagu et al. (1979)
13	Harding and Whitton (1978)
19-80	U. S. Environmental Protection Agency (1975b)
227-7490	U. S. Environmental Protection Agency (1977)

concentration was within the ranges found in contaminated freshwater sediments according to available literature (Table 8).

95. Iron. Total iron content of the sediments ranged from 7.02 to 291.31 mg g^{-1} and averaged 48.01 mg g^{-1}. The total iron concentration was within the range found in available literature for freshwater sediments (Table 9) except for the sediments DE 1, IN 2, and IN 3, which were higher than those reported.

Table 8

Total Copper Content of Some Freshwater Sediments

Concentration or Range $\mu g\ g^{-1}$	Literature Reference
6-19	U. S. Environmental Protection Agency (1975a)
24-175	U. S. Environmental Protection Agency (1977)
26-58	Williams et al. (1978)
43.7-710	Mudroch and Capobianco (1978)
56-260	U. S. Environmental Protection Agency (1975b)
104-146	Nriagu et al. (1979)

Table 9

Total Iron Content of Some Freshwater Sediments

Concentration or Range $mg\ g^{-1}$	Literature Reference
5.9-61.0	U. S. Environmental Protection Agency (1975a)
10.0-18.0	Mudroch and Capobianco (1978)
17.0-36.0	U. S. Environmental Protection Agency (1975b)
33.0-36.0	Williams et al. (1978)

96. Manganese. Total manganese content of the freshwater sediments ranged from 164 to 2503 $\mu g\ g^{-1}$ and averaged 748 $\mu g\ g^{-1}$. Total manganese content of sediment from IN 3 was the highest of all (2503 $\mu g\ g^{-1}$). The range of total manganese content of the sediments was within the range reported in the literature (Table 10).

97. Arsenic. The total arsenic content of the sediments ranged from <0.001 to 316.5 $\mu g\ g^{-1}$ and averaged 30.1 $\mu g\ g^{-1}$. Arsenic data for freshwater sediment are scarce. Kobayashi and Lee (1978) studied arsenic accumulation in sediments of several Wisconsin lakes and found that the arsenic content of the sediments (top 20 cm) ranged from as low as 9 $\mu g\ g^{-1}$ to as high as 700 $\mu g\ g^{-1}$. The arsenic concentrations reported in this study were not, therefore, outstandingly high (Table 11).

Table 10

Total Manganese Content of Some Freshwater Sediments

Concentration or Range $\mu g\ g^{-1}$	Literature Reference
160-880	U. S. Environmental Protection Agency (1975a)
390-700	Mudroch and Capobianco (1978)
510-810	U. S. Environmental Protection Agency (1975b)
1700-2400	Williams et al. (1978)

Table 11

Total Arsenic Content of Some Freshwater Sediments

Concentration or Range $\mu g\ g^{-1}$	Literature Reference
2-14	U. S. Environmental Protection Agency (1975b)
2-87	U. S. Environmental Protection Agency (1975a)
9-700	Kobayashi and Lee (1978)
350-9660	U. S. Environmental Protection Agency (1977)

98. Mercury. The total mercury content of the sediments ranged from <0.009 to 1.50 $\mu g\ g^{-1}$ and averaged 0.37 $\mu g\ g^{-1}$. The mercury levels found in this study were within the range of the mercury content of several freshwater sediments reported in the literature (Table 12). The unusually high mercury value of 19.3 $\mu g\ g^{-1}$ reported by Turner and Lindberg (1978) was for a sediment immediately downstream from a chloralkali plant.

99. Nickel. The total nickel content of the freshwater sediments ranged from 8.2 to 152.8 $\mu g\ g^{-1}$ and averaged 48.3 $\mu g\ g^{-1}$. Total nickel content of the sediments was within the range of nickel-contaminated freshwater sediments reported in the literature (Table 13).

100. Chromium. The total chromium content of the sediments ranged from 8.2 to 1974.3 $\mu g\ g^{-1}$ and averaged 236.0 $\mu g\ g^{-1}$. This range was within the total chromium range of contaminated freshwater sediments

Table 12

Total Mercury Content of Some Freshwater Sediments

Concentration or Range $\mu g\ g^{-1}$	Literature Reference
0.0-0.1	U. S. Environmental Protection Agency (1975b)
0.0175	Khalid, Gambrell, and Patrick (1975)
0.0122-0.1026	Gardner (1978)
0.02-1.8	U. S. Environmental Protection Agency (1977)
<0.1-0.2	U. S. Environmental Protection Agency (1975a)
0.13-19.3	Turner and Lindberg (1978)

Table 13

Total Nickel Content of Some Freshwater Sediments

Concentration or Range $\mu g\ g^{-1}$	Literature Reference
<8-26	U. S. Environmental Protection Agency (1975a)
9.2-24.1	Mudroch and Capobianco (1978)
40-6070	U. S. Environmental Protection Agency (1977)
55-170	U. S. Environmental Protection Agency (1975b)

reported in the literature (Table 14), except for the extremely high chromium content of 1974.3 $\mu g\ g^{-1}$ for IN 3.

101. Lead. The total lead content of the freshwater sediments ranged from 25 to 1521 $\mu g\ g^{-1}$ and averaged 310 $\mu g\ g^{-1}$. The total lead content of the freshwater sediments was within that of contaminated freshwater sediments reported in the literature (Table 15), except for the 1521 $\mu g\ g^{-1}$ for IN 3.

DTPA extractable heavy metals

102. The concentration of heavy metals in DTPA extracts of original reduced sediment and of air-dried sediment is presented in Table 16. The significance of the differences in concentration of heavy metals in DTPA extracts between the two sediment conditions was determined using

Table 14

Total Chromium Content of Some Freshwater Sediments

Concentration or Range $\mu g\ g^{-1}$	Literature Reference
4-31	U. S. Environmental Protection Agency (1975a)
40-173	U. S. Environmental Protection Agency (1977)
56-370	U. S. Environmental Protection Agency (1975b)

Table 15

Total Lead Content of Some Freshwater Sediments

Concentration or Range $\mu g\ g^{-1}$	Literature Reference
<10-74	U. S. Environmental Protection Agency (1975a)
11-1365	U. S. Environmental Protection Agency (1977)
90-325	U. S. Environmental Protection Agency (1975b)

the Least Significant Difference method at probability $\alpha = 0.05$ ($LSD_{0.05}$). In order for a difference to be real (significantly different), it has to exceed the indicated LSD's.

103. Air drying the freshwater sediments had an effect on DTPA extractable heavy metals. The zinc concentration in DTPA extracts of air-dried sediments was higher than that from original sediments in 6 out of 15 cases; that of cadmium in 7 out of 15 cases; that of copper in 8 out of 15 cases; that of manganese in 7 out of 15 cases; only 2 out of 15 cases for nickel; 9 out of 15 cases for chromium; and 7 out of 15 cases for lead. Extraction of the original sediments resulted in heavy metal concentrations greater than that of air-dried sediments for 1 out of 15 cases for cadmium; 2 out of 15 cases for manganese; 6 out of 15 cases for nickel; 2 out of 15 cases for chromium; and 6 out of 15 cases for lead. No differences between air-dried and original sediments were found for DTPA extractable mercury.

Table 16

Concentration of Heavy Metals in DTPA Extracts of Reduced (Flooded) and of Reconstituted, Air-Dried (Upland) Freshwater Sediments

Location*/	Concentration $\mu g\ g^{-1}$									
	Zn		Cd		Cu		Fe		Mn	
Site	Flooded	Upland	Flooded	Upland	Flooded	Upland	Flooded	Upland	Flooded	Upland
DE 1	48.1	173.1	<0.0005	6.30	<0.025	57.37	910	198	131.4	140.5
2	276.6	255.1	4.89	4.15	13.00	98.33	921	840	13.1	55.0
3	1.8	13.6	0.30	0.03	8.45	4.72	394	296	34.3	52.2
MC 1	179.9	130.0	3.33	2.92	18.04	16.29	867	348	29.1	51.6
2	180.1	811.6	0.83	25.26	0.04	64.70	1013	426	53.0	78.6
3	5.4	743.1	<0.0005	31.25	<0.005	56.45	1420	462	37.4	107.2
IN 1	205.8	227.0	0.53	1.10	<0.005	16.61	1044	742	47.8	168.3
2	48.3	512.9	<0.0005	3.11	<0.005	28.69	1194	609	63.4	202.7
3	10.6	1339.2	<0.0005	5.44	<0.005	76.27	1363	171	11.8	45.2
MW 1	144.6	265.6	3.39	6.08	0.79	43.81	1087	539	52.7	104.3
2	21.1	14.9	0.82	0.73	11.04	6.93	883	462	80.8	99.0
3	14.5	14.4	0.50	0.53	8.43	5.63	832	542	62.8	81.4
ME 1	5.3	6.1	0.40	0.19	<0.005	2.41	850	205	146.8	42.2
2	5.3	27.1	<0.0005	0.64	4.12	7.39	587	402	71.2	131.5
3	6.3	33.5	<0.0005	2.72	<0.005	10.93	1153	783	429.1	239.
$LSD_{0.05}$**	43.8		1.10		12.00		85		24.0	

	Concentration, $\mu g\ g^{-1}$									
	As		Hg		Ni		Cr		Pb	
	Flooded	Upland	Flooded	Upland	Flooded	Upland	Flooded	Upland	Flooded	Upland
DE 1	<0.005	CI†	<0.001	0.001	14.40	5.02	0.08	0.10	80.4	140.1
2	0.169	CI	<0.001	<0.001	60.74	28.51	2.25	1.21	181.0	138.9
3	<0.005	CI	0.001	<0.001	2.68	0.64	0.00	0.16	5.2	2.3
MC 1	<0.005	CI	<0.001	<0.001	IS††	IS	IS	IS	IS	IS
2	<0.005	CI	<0.001	<0.001	30.42	17.72	0.28	0.78	43.1	86.1
3	<0.005	CI	<0.001	<0.001	75.45	37.47	0.54	1.09	44.7	120.9
IN 1	<0.005	CI	<0.001	<0.001	4.43	2.82	0.27	0.22	41.6	33.1
2	<0.005	CI	<0.001	<0.001	4.24	23.39	0.25	1.69	36.8	185.2
3	<0.005	CI	<0.001	<0.001	17.87	1.74	2.51	0.15	5.6	47.0
MW 1	0.122	CI	0.001	<0.001	7.43	8.67	0.79	1.26	261.9	325.2
2	<0.005	CI	0.001	<0.001	2.82	4.53	0.05	0.36	7.8	5.6
3	<0.005	CI	<0.001	<0.001	2.09	4.33	0.10	0.40	8.8	14.4
ME 1	<0.005	CI	0.001	<0.001	0.85	0.56	0.07	0.17	6.0	11.2
2	0.278	CI	<0.001	0.001	1.39	2.67	0.06	0.63	18.8	31.6
3	131.000	37.200	<0.001	<0.001	2.80	4.84	0.54	1.16	5.3	206.9
$LSD_{0.05}$**	--		--		1.96		0.14		25.7	

* Abbreviations are the same as those listed in Figures 5-7.
** $LSD_{0.05}$ = Least Significant Difference at α = 0.05.
† CI = Chemical interference.
†† IS = Insufficient sediment for extraction and subsequent analysis.

104. The arsenic concentration in the air-dried sediments could not be determined because of chemical interference (CI). No explanation of the interference could be found. This would imply, however, that DTPA would not be the best choice for determining sediment arsenic.

105. Chelating agents (natural or synthetic) play an important role in overcoming the rate-limiting steps of solubilization and adsorbed phase diffusion that are mainly responsible for the movement and plant availability of heavy metals in alkaline and calcareous soils. Consequently, an organic chelate may be a good estimator of plant available heavy metals.

106. A recent study by Lee, Sturgis, and Landin (1978) investigated the relationship of sediment extractable heavy metals to plant uptake of heavy metals. Four extraction procedures thought to have the potential in predicting heavy metal uptake by marsh plants from dredged material were evaluated and included water soluble, exchangeable, dilute acid extractable, and DTPA extractable heavy metals. Lee, Sturgis, and Landin (1978) concluded that the DTPA extraction procedure gave the best correlations of sediment zinc, cadmium, and copper and to a lesser extent with lead and chromium to saltmarsh plant contents of these heavy metals.

107. Lindsay and Norvell (1978) also used a DTPA soil test to predict availability of zinc, iron, manganese, and copper for plant uptake on near-neutral and calcareous soils. DTPA was chosen because it offered the most favorable combination of stability constants for the simultaneous complexing of iron, zinc, copper, and manganese. Lindsay and Norvell (1978) designed the DTPA extraction solution to specifically avoid excessive dissolution of calcium carbonate (prevalent in calcareous soils) with the release of occluded heavy metals. This DTPA soil test successfully predicted crop (corn) response on a number of Colorado soils to applied zinc, iron, and manganese fertilizers.

108. Severson, Gough, and McNeal (1977) investigated the availability of several heavy metals in soils to native plants of the northern Great Plains. They assessed the relationship between concentration of heavy metals (cadmium, copper, iron, manganese, nickel, lead, and

zinc) in two plant species (western wheatgrass and silver sagebrush), and soil extractable heavy metals. The extractants studied were DTPA, ethylenediaminetetraacetic acid (EDTA), and ammonium oxalate. They found that, based on simple correlation between elemental plant concentration and DTPA extractable heavy metals, only cadmium, copper, and nickel were correlated with sagebrush tissue concentration of these elements.

109. In the present study, several DTPA extractable heavy metals were significantly more extractable from the upland sediments than from the flooded sediments. Most DTPA extraction procedures referenced above have been developed using air-dried and ground soils. Moisture status (wet/dry) has been shown by several investigations to affect DTPA extractable heavy metals. Gogan (1975) found that drying greatly increased DTPA extractable zinc. Silviera and Sommers (1977) found that DTPA extractable copper, zinc, cadmium, and lead were greater from sludges that had been air dried compared to wet sludges and suggested that the increased DTPA extractable heavy metals were due to transformations of zinc, copper, cadmium, and lead compounds during the drying process. When the sludges were added to soil and incubated, DTPA extractable copper, zinc, and cadmium increased with time, while that of lead remained constant. Silviera and Sommers (1977) explained that this increase in DTPA extractable heavy metals was due to dissolution of metal precipitates, oxidation of metal sulfides, and release of metals complexed with sludge organic matter as the organic matter decomposed.

110. Increased solubility of heavy metals could have occurred when the sediments under reduced conditions were allowed to drain and become oxidized (Patrick 1964). This increase in solubility could have occurred as a result of ferrous iron being oxidized to ferric iron, which releases hydrogen ions. The pH of the sediments would not necessarily have decreased if large amounts of alkaline carbonates were present (as was the case for most sediments) to neutralize the excess hydrogen produced.

111. Increased solubility of heavy metals could also have occurred as heavy metal sulfides were oxidized to more soluble sulfate compounds. Even though a pH decrease was not observed after air drying

the sediments (apparently enough alkaline carbonates were present to neutralize excess hydrogen produced), this does not mean that oxidization of sulfide had not occurred.

112. The protective effect of organic matter in reducing toxicity of heavy metals to plants is fairly well established (Chaney 1973). This protective effect is probably due to the heavy metals forming stable complexes with the organic matter present in the soil (Ellis and Knezek 1972; Stevenson and Ardakani 1972). The stabilities of the heavy metal-organic matter complexes appear to be greater than heavy metal-DTPA complexes (Randall, Schulte, and Corey 1976; Schnitzer and Hansen 1970; MacLean and Dekker 1978). This can be inferred from several studies because DTPA extractable heavy metals have been shown to increase with time (MacLean and Dekker 1978; Giordano, Mays, and Behel 1979; Sinha and Prasad 1977). Consequently, as the organic matter decomposed, the heavy metals from heavy metal-organic matter complexes were available for complexation by DTPA.

113. The majority of the data presented shows that DTPA extracted greater quantities of heavy metals from the upland sediments than from the flooded sediments. This probably reflects heavy metal-organic matter complexes being decomposed as the sediments became oxidized during the air-drying stage of sediment preparation. It is known that decomposition of organic matter occurs to a greater extent and much quicker in aerobic (upland-oxidized) environments than in anaerobic (flooded-reduced) environments (Alexander 1977). Consequently, the heavy metals became more available for complexation by DTPA as shown in Table 16.

114. Extraction of the sediments using DTPA indicated that plant uptake of zinc, cadmium, copper, manganese, chromium, and lead should be greater from upland sediments than from flooded sediments, while plant uptake of iron, arsenic, and nickel should be greater from flooded sediments than from upland sediments.

Interstitial water
extractable heavy metals

115. Heavy metal concentrations in IW extracted from the freshwater sediments are presented in Tables 17-21. Heavy metal

Table 17

Heavy Metal Concentrations in the Interstitial Water of Sediments from Three Sites in the Detroit (DE) River, Michigan

Location*/ Site	Sampling Time**	Treatment†	Concentration, $\mu g\ cm^{-3}$ Zn	Cd	Cu	Fe	Mn	As	Hg	Ni	Cr	Pb
DE 1	Initally	Flooded	<0.004	0.0002	0.0260	0.26	0.07	0.013	<0.0002	0.011	0.006	0.000
		Upland	0.15	0.0029	0.1887	0.13	0.10	0.006	<0.0002	0.106	0.003	0.002
	End	Flooded	0.01	0.0008	<0.001	0.60	0.26	<0.001	0.0002	IS††	IS	IS
DE 2	Initially	Flooded	<0.004	<0.0001	<0.001	0.41	0.14	0.008	<0.0002	0.268	0.013	0.002
		Upland	0.63	0.0080	0.2837	0.39	1.25	0.002	0.0002	0.486	0.012	0.013
	End	Flooded	0.09	0.0055	<0.001	19.02	0.69	0.012	<0.0002	IS	IS	IS
DE 3	Initially	Flooded	0.77	IS	0.0110	0.31	0.15	IS	IS	0.009	0.013	0.002
		Upland	0.22	0.0018	0.0210	0.28	0.47	<0.001	IS	IS	IS	IS
	End	Flooded	0.06	0.0010	0.0001	0.04	0.01	<0.001	IS	IS	IS	IS
$LSD_{0.05}$‡			0.06	0.1980	0.0424	2.23	0.96	0.396		0.173	0.020	0.025

* Abbreviations are the same as those listed in Figures 5-7.

** Water samples were taken initially and at the end of the growth period.

† Sediments under a reduced (flooded) condition and sediments that had been reconstituted from an air-dried condition (upland).

†† IS = Insufficient sample for analysis.

‡ $LSD_{0.05}$ = Least Significant Difference at $\alpha = 0.05$.

Table 18

Heavy Metal Concentrations in the Interstitial Water of Sediments from Three Sites in Michigan City Harbor (MC), Indiana

Location*/ Site	Sampling Time**	Treatment†	Concentration, $\mu g\ cm^{-3}$									
			Zn	Cd	Cu	Fe	Mn	As	Hg	Ni	Cr	Pb
MC 1	Initally	Flooded	0.0001	0.0001	0.0027	2.11	0.94	0.001	0.0002	IS††	IS	IS
		Upland	0.54	0.0090	0.0647	0.25	0.85	0.001	IS	IS	IS	IS
	End	Flooded	0.23	0.0062	0.0010	7.74	2.26	0.001	IS	IS	IS	IS
MC 2	Initially	Flooded	0.06	0.0005	0.0047	31.89	1.81	IS	IS	0.034	0.007	0.002
		Upland	3.09	0.0311	0.2837	0.24	2.90	IS	IS	0.383	0.029	0.023
	End	Flooded	0.19	0.0012	0.001	27.45	6.23	IS	IS	IS	IS	IS
MC 3	Initially	Flooded	0.10	0.0008	0.0090	23.75	2.10	IS	IS	0.346	0.013	0.000
		Upland	2.21	0.0581	0.2250	0.21	3.25	IS	IS	0.705	0.043	0.024
	End	Flooded	0.04	0.0007	0.001	49.22	5.20	IS	IS	IS	IS	IS
$LSD_{0.05}$‡			0.06	0.1980	0.015	0.79	0.34	0.14	--	0.061	0.007	0.009

* Abbreviations are the same as those listed in Figures 5-7.

** Water samples were taken initially and at the end of the growth period.

† Sediments under a reduced (flooded) condition and sediments that had been reconstituted from an air-dried condition (upland).

†† IS = Insufficient sample for analysis.

‡ $LSD_{0.05}$ = Least Significant Difference at $\alpha = 0.05$.

Table 19

Heavy Metal Concentrations in the Interstitial Water of Sediments from Three Sites in Indiana Harbor (IN), Indiana

Location*/ Site	Sampling Time**	Treatment†	Concentration, μg cm^{-3} Zn	Cd	Cu	Fe	Mn	As	Hg	Ni	Cr	Pb
IN 1	Initally	Flooded	0.06	0.0018	0.0123	0.51	0.57	0.022	0.0002	0.017	0.004	<0.0005
		Upland	0.60	0.0013	0.0645	0.28	1.60	<0.001	IS††	IS	IS	IS
	End	Flooded	0.50	0.0004	<0.001	25.0	5.52	<0.001	IS	IS	IS	IS
IN 2	Initially	Flooded	0.10	0.0008	0.0357	0.95	0.11	0.616	IS	0.007	0.001	0.001
		Upland	1.9[illegible]	0.0062	0.1020	0.69	9.60	0.001	IS	0.418	0.047	<0.0005
	End	Flooded	0.30	0.0006	<0.001	15.88	2.43	0.002	IS	IS	IS	IS
IN 3	Initially	Flooded	0.12	0.0006	0.0520	2.40	0.14	0.001	IS	0.038	0.015	0.003
		Upland	14.56	0.0254	0.9300	0.72	5.98	0.013	IS	0.020	0.006	0.005
	End	Flooded	0.06	0.0004	<0.001	53.52	2.21	0.003	IS	IS	IS	IS
$LSD_{0.05}$‡			0.02	0.007	0.015	0.79	0.34	0.14	--	0.061	0.007	0.009

* Abbreviations are the same as those listed in Figures 5-7.
** Water samples were taken initially and at the end of the growth period.
† Sediments under a reduced (flooded) condition and sediments that had been reconstituted from an air-dried condition (upland).
†† IS = Insufficient sample for analysis.
‡ $LSD_{0.05}$ = Least Significant Difference at $\alpha = 0.05$.

Table 20

Heavy Metal Concentrations in the Interstitial Water of Sediments from Three Sites in Milwaukee Harbor (MW), Wisconsin

Location*/ Site	Sampling Time**	Treatment†	Concentration, $\mu g\ cm^{-3}$									
			Zn	Cd	Cu	Fe	Mn	As	Hg	Ni	Cr	Pb
MW 1	Initally	Flooded	0.04	0.0001	0.0197	8.23	1.31	<0.001	<0.0002	0.019	0.010	<0.0005
		Upland	0.50	0.0049	0.1383	0.16	1.19	0.004	IS††	0.133	0.069	0.008
	End	Flooded	0.12	0.0017	<0.001	19.59	2.46	<0.001	IS	IS	IS	IS
MW 2	Initially	Flooded	<0.004	0.0001	0.0053	0.11	0.50	IS	IS	0.001	0.007	<0.0005
		Upland	0.20	0.0012	0.0170	0.14	0.24	IS	IS	0.108	0.054	0.017
	End	Flooded	0.30	0.0006	<0.001	<0.001	0.04	IS	IS	IS	IS	IS
MW 3	Initially	Flooded	0.01	0.0002	0.0153	0.30	0.51	IS	IS	0.000	0.007	<0.0005
		Upland	0.21	0.0010	0.0157	0.16	0.16	IS	IS	0.130	0.052	0.019
	End	Flooded	0.21	0.0015	<0.001	0.03	0.05	IS	IS	IS	IS	IS
$LSD_{0.05}$‡			0.02	0.007	0.015	0.79	0.34	0.14	--	0.061	0.007	0.009

* Abbreviations are the same as those listed in Figures 5-7.
** Water samples were taken initially and at the end of the growth period.
† Sediments under a reduced (flooded) condition and sediments that had been reconstituted from an air-dried condition (upland).
†† IS = Insufficient sample for analysis.
‡ $LSD_{0.05}$ = Least Significant Difference at $\alpha = 0.05$.

Table 21

Heavy Metal Concentrations in the Interstitial Water of Sediments from Three Sites in the Menominee River (ME), Wisconsin

Location*/ Site	Sampling Time**	Treatment†	Concentration, $\mu g\ cm^{-3}$									
			Zn	Cd	Cu	Fe	Mn	As	Hg	Ni	Cr	Pb
ME 1	Initally	Flooded	0.20	0.0029	<0.001	3.10	9.54	0.697	0.0002	0.019	0.010	<0.0005
		Upland	0.23	0.0012	0.0480	0.36	3.43	IS††	<0.133	0.069	0.008	
	End	Flooded	0.09	0.0096	<0.001	8.53	6.59	0.006	IS	IS	IS	IS
ME 2	Initially	Flooded	0.02	0.00013	0.0553	3.30	3.88	0.082	IS	0.001	0.007	<0.0005
		Upland	0.32	0.00017	0.0237	0.40	5.09	0.015	IS	0.108	0.054	0.017
	End	Flooded	0.02	0.0027	<0.001	17.86	3.46	0.019	0.0002	IS	IS	IS
ME 3	Initially	Flooded	0.03	0.0003	0.0123	70.62	27.23	37.58	<0.0002	0.000	0.007	<0.0005
		Upland	0.27	0.0023	0.1587	7.27	1.20	3.95	0.0002	0.130	0.052	0.019
	End	Flooded	0.05	<0.0001	<0.001	66.35	15.60	11.79	0.0002	IS	IS	IS
$LSD_{0.05}$‡			0.02	0.007	0.015	0.79	0.34	0.14	--	0.061	0.007	0.009

* Abbreviations are the same as those listed in Figures 5-7.

** Water samples were taken initially and at the end of the growth period.

† Sediments under a reduced (flooded) condition and sediments that had been reconstituted from an air-dried condition (upland).

†† IS = Insufficient sample for analysis.

‡ $LSD_{0.05}$ = Least Significant Difference at $\alpha = 0.05$.

concentrations in IW from original reduced sediments were compared to heavy metal concentrations in reconstituted IW of the air-dried sediment. This was done to see if air drying resulted in increased heavy metal concentration in the resultant extracts. Also, the effect of time upon heavy metal concentration in the IW of flooded sediments was evaluated. The data for this comparison can be obtained by comparing initial IW heavy metal concentration with that in IW extracts at the end of the growth period.

116. Air drying the sediments resulted in higher concentrations of several of the heavy metals in IW extracts from the upland sediments than in IW from the flooded sediments. Zinc concentration was consistently higher in IW from air-dried sediments while iron was consistently higher in IW from flooded sediments. Copper, manganese, nickel, chromium, and lead concentrations all tended to be higher in the IW from upland sediments compared to flooded sediments. Although not always statistically significant, cadmium concentration was generally higher in the IW from the upland sediments. Arsenic and mercury concentrations were generally near or below detection limits in all sediments except those from ME. The sediment from ME 3 had a high total arsenic concentration of >300 $\mu g\ g^{-1}$ (Table 5). The arsenic concentration was apparently ten times higher in IW from the flooded sediment than from the air-dried sediment from ME 3 (Table 21).

117. Heavy metal concentrations in IW samples were determined because researchers have suggested that if an element was present in the IW (or soil solution), then it could be immediately available for plant uptake. This assumes that the element moves along with the water in the transpiration stream. Hossner, Freeouf, and Folsom (1973), using the soil solution extraction method of Hossner and Phillips (1973), showed that if the soil solution phosphorus concentration was greater than 0.1 $\mu g\ g^{-1}$, maximum yields of rice were obtained. This requirement was related to phosphorus moving with the transpiration stream. Reddy and Patrick (1977b) indicated that if cadmium was present in the soil solution, it was moving into the rice plant with the transpiration stream. Bingham et al. (1976) indicated that continuous flooded

conditions resulted in a reducing environment favorable for the formation of soluble forms of iron and manganese that accumulated in the soil solution and, thus, became more readily available for uptake by rice. Bingham et al. (1976) also showed that cadmium, copper, and zinc concentrations in saturation extracts (like IW) of nonflood-managed soils were greater than those in flood-managed soils. The IW heavy metal concentrations would, therefore, suggest that zinc, cadmium, copper, manganese, nickel, chromium, and lead concentrations should be greater in the plants grown on upland sediments than in the plants grown on those same sediments flooded.

Plant uptake of heavy metals

118. Aboveground. The concentration of heavy metals in aboveground tissues of *C. esculentus* grown in freshwater sediments under flooded and upland environments is presented in Table 22. Concentration of zinc in the aboveground tissue was higher in plants grown in upland sediments in only 6 out of 15 sediments; in the other 9 sediments no difference in zinc concentration was apparent. Cadmium concentration in the aboveground tissue was higher in plants grown in upland sediments in 7 out of 15 sediments; in the remaining 8 sediments the cadmium concentration was equal in the aboveground tissue in both flooded and upland sediments. Copper concentration in the aboveground tissue was higher in plants grown in upland sediments in only 3 out of 15 sediments, equal in 10 out of 15 sediments, and higher in flooded sediments in only 2 out of 15 sediments. Iron concentration in the aboveground tissue was equal between plants grown in upland and flooded sediments. Manganese concentration, however, was higher in plant tissue from upland sediments in 9 out of 15 sediments and higher in only 4 out of 15 flooded sediments. Mercury concentration in the aboveground plant tissue was equal between both upland and flooded sediments in 13 out of 15 sediments and greater in only 2 out of 15 upland sediments. Concentration of nickel in aboveground tissue was higher in plants grown in upland sediments in only 4 out of 15 sediments, higher in flooded sediments in only 2 out of 15 sediments, and equal in the rest. Chromium concentration in aboveground plant tissue was equal between upland and flooded sediments

Table 22

Concentration of Heavy Metals in Aboveground Tissue of *C. esculentus* Grown in Freshwater Sediments Under Reduced (Flooded) and Oxidized (Upland) Environments

Location*/ Site	Zn Flooded	Zn Upland	Cd Flooded	Cd Upland	Cu Flooded	Cu Upland	Fe Flooded	Fe Upland	Mn Flooded	Mn Upland
	Concentration, $\mu g\ g^{-1}$									
DE 1	75.5	75.8	0.77	2.81	3.97	2.67	27.9	41.8	174	163
2	96.8	122.8	0.79	6.49	0.89	2.78	30.9	24.9	199	665
3	151.5	150.8	0.23	1.17	1.68	3.42	36.4	21.8	662	401
MC 1	63.3	259.6	1.31	17.64	1.63	5.83	35.5	33.9	514	345
2	70.4	168.3	2.81	20.84	2.27	5.99	35.2	48.9	371	586
3	56.7	84.5	2.50	7.80	2.67	3.72	73.1	88.3	276	419
IN 1	34.8	112.8	0.19	1.95	1.09	4.31	25.5	33.0	678	1322
2	51.8	154.0	0.51	6.34	0.23	2.91	29.9	21.5	619	2291
3	63.5	172.9	0.25	1.27	1.96	2.63	66.5	24.8	261	454
MW 1	48.8	256.4	1.24	12.60	3.53	6.53	51.8	66.0	390	682
2	87.8	83.3	0.41	1.84	2.62	2.88	26.7	24.2	586	507
3	84.9	58.0	0.32	0.87	2.35	2.19	27.5	30.6	480	139
ME 1	29.6	23.8	0.82	1.45	8.40	3.25	25.3	24.9	689	259
2	76.5	80.8	0.36	1.44	3.78	2.10	35.6	28.4	302	552
3	0.2	17.3	0.47	9.57	7.80	4.59	67.3	27.8	549	1096
$LSD_{0.05}$**	40.7		3.65		3.05		49.5		114	

Location*/ Site	As Flooded	As Upland	Hg Flooded	Hg Upland	Ni Flooded	Ni Upland	Cr Flooded	Cr Upland	Pb Flooded	Pb Upland
	Concentration, $\mu g\ g^{-1}$									
DE 1	<0.025	<0.025	0.024	0.072	<0.08	<0.08	0.212	0.261	1.345	1.220
2	<0.025	<0.025	0.038	0.008	0.44	0.33	0.182	0.394	2.245	1.629
3	<0.025	<0.025	0.004	0.013	<0.08	<0.08	0.207	0.094	0.891	1.237
MC 1	<0.025	<0.025	0.008	0.075	1.87	0.67	3.057	<0.025	0.670	1.179
2	<0.025	<0.025	0.053	0.036	2.70	2.57	2.827	5.211	1.370	1.229
3	<0.025	<0.025	0.044	0.018	2.60	3.41	3.490	2.180	1.162	0.866
IN 1	<0.025	<0.025	0.034	0.005	<0.08	<0.08	0.361	0.386	0.670	0.991
2	<0.025	<0.025	0.015	0.028	<0.08	<0.08	0.594	0.894	0.754	1.004
3	<0.025	<0.025	0.025	0.045	0.11	3.29	0.711	0.707	0.816	1.129
MW 1	<0.025	<0.025	0.003	0.013	0.12	0.66	4.527	0.144	1.037	1.179
2	<0.025	<0.025	0.010	0.020	<0.08	<0.08	0.077	0.227	0.754	1.212
3	<0.025	<0.025	0.013	0.013	0.10	<0.08	0.244	0.511	0.995	1.495
ME 1	<0.025	<0.025	0.005	0.008	<0.08	<0.08	0.561	0.124	1.079	1.062
2	<0.025	<0.025	0.005	0.012	0.42	<0.08	0.361	0.577	1.254	1.279
3	10.700	1.450	0.050	0.016	<0.08	3.06	1.177	0.611	0.539	1.104
$LSD_{0.05}$**	--		0.045		0.263		1.923		0.424	

* Abbreviations are the same as those listed in Figures 5-7.

** $LSD_{0.05}$ = Least Significant Difference at α = 0.05.

in 12 out of 15 sediments, greater in plants grown in 2 out of 15 flooded sediments, and greater in plants grown in upland sediments in only one sediment (MC 2). Lead concentration in aboveground plant tissue was greater from plants grown in upland sediments in only 4 out of 15 sediments while plants grown in only 1 out of 15 sediments had higher lead concentration under a flooded environment. The rest had equal lead concentrations in both conditions.

119. Concentration of arsenic in aboveground tissue was above detectable limits in plants grown in sediment from only one site (ME 3). The arsenic concentration of aboveground tissue in plants grown in sediment from that site was higher under flooded conditions than it was under upland conditions.

120. There is considerable information on heavy metal uptake by agricultural plants on soils and, as stated by Lee, Sturgis, and Landin (1976), on waste-amended soils. However, the study by Lee, Sturgis and Landin (1976) is the only specific reference found on heavy metal uptake by *C. esculentus*.

121. A general comparison of heavy metal-plant relationships obtained in the present study can be made with heavy metal-plant relationships in rice literature available.

122. Cottenie, Dhaese, and Camerlynck (1976) gave the following plant concentrations of heavy metals that caused external symptoms of phytotoxicity to a sedge (*C. esculentus* is a sedge and is a member of the family *Cyperacae* (Fernald 1950)): zinc, 95 ppm; cadmium, 2 ppm; copper, 574 ppm; manganese, 15 ppm; nickel, 23 ppm; and lead, 104 ppm. Comparison of the data obtained in the present study with that of Cottenie, Dhaese, and Camerlynck (1976) reveals that zinc, cadmium, and manganese concentrations were greater than they reported with no apparent phytotoxicity symptoms occurring.

123. Jugsujinda and Patrick (1977) investigated heavy metal uptake by rice (*Oryza sativa* L. Cv. *Saturn*) at several different controlled redox potentials and pH conditions. They found that redox and pH had a significant effect on heavy metal uptake. Their data indicated that iron and manganese were greater in plants grown under anaerobic

conditions (flooded) compared to aerobic conditions (upland). For example they found 91 μg g^{-1} iron and 182 μg g^{-1} manganese for anaerobic versus 39 μg g^{-1} iron and 32 μg g^{-1} manganese for aerobic, both at pH 7. Zinc was, however, greater in plants grown under aerobic conditions (22 μg g^{-1} zinc for aerobic versus 9 μg g^{-1} zinc for anaerobic, both at pH 7). Similar relative relationships were obtained at pH 8 even though the absolute values were half of those at pH 7.

124. Bingham et al. (1976) investigated heavy metal availability to rice under flood and nonflood conditions. They found that several heavy metal concentrations (zinc, iron, and manganese) in rice leaves were greater under flooded conditions than nonflooded conditions; cadmium concentration in rice leaves was greater under nonflooded conditions. However, when total uptake (concentration times yield) was considered, total uptake by plants grown in flooded conditions was significantly greater than that of upland conditions. These data indicate a dilution effect and do not indicate a real increase in plant uptake of cadmium. Both uptake and accumulation of copper were found to be independent of water treatment (i.e., flood versus nonflood) (Bingham et al. (1976).

125. Reddy and Patrick (1977b) found that cadmium and lead uptake by rice (*Oryza sativa* L.) was significantly affected by redox condition of the growth media (a soil suspension). They found that cadmium concentration in the plant tissue increased as redox potential increased (more oxidized). Lead concentration was increased in plant tissue as the redox potential decreased (more reduced).

126. When considering concentration of heavy metals in plant tissue, dilution due to enhanced plant growth (dilution effect) must be considered. Wallace et al. (1977) implied that the cadmium toxicity found in their experiment was real and not due just to a concentration effect resulting from decreased yields. Street, Sabey, and Lindsey (1978) also indicated that a dilution effect resulting from increased yields could occur and mask a real cadmium toxicity. Miller, Hassett, and Koeppe (1977) explained that a cadmium increase in plant tissue due to lead was a result of decreased plant growth due to the lead (i.e., concentration effect resulting from decreased yields). Data presented

in Table 23 show that increased concentration of zinc (DE 2, IN 1-3), cadmium (DE 2 and IN 2), copper (IN 1, ME 3), manganese (DE 2, MC 2, MC 3, IN 1, IN 3, MW 1), chromium (MC 2), and lead (MC 1, MW 2, MW 3) in plants grown in the upland sediments was due to decreased plant growth (Table 4). Apparently, only a certain amount of these metals was taken up by *C. esculentus* and, as the amount of plant material increased, the effective heavy metal concentration decreased.

127. Belowground. While *C. esculentus* can be propagated by both seeds and tubers, tubers are the principal means (Bell et al. 1962). One tuber may produce 1900 plants and 6900 tubers in 1.6 sq m in 1 year (Tumbleson and Kommedahl 1961). Tubers of *C. esculentus* are a favorite food of wildlife and as such could represent a significant source of contaminant entry into the food chain. For this reason, the heavy metal content of the tubers was determined (Table 24).

128. Sediment redox status seemed to affect tuber heavy metal concentration somewhat differently than that of the aboveground tissue. Concentration of zinc in tuber tissue was greater in plants grown in upland sediments compared to flooded sediments in only 2 out of 15 sediments (MC 2 and ME 3), greater in plants from flooded sediments in 2 out of 15 sediments (DE 3 and IN 3), and equal in the other 11 sediments. Cadmium concentration was greater in tubers from plants grown under upland sediment conditions compared to flooded sediment conditions in 7 out of 15 sediments, greater under flooded sediments in only 1 out of 15 sediments (DE 3), and equal in the other 7 sediments. Copper concentration in tubers from plants grown in upland sediments was greater than those grown in flooded sediments in only 2 out of 15 sediments (MC 1 and MW 2) while the rest (13 out of 15) were equal between the two sediment conditions. Iron concentration in tubers from plants grown in flooded sediments was greater than that in upland sediments in 8 out of 15 sediments while the remainder were equal between sediment conditions. Manganese concentration in the tubers behaved like iron, in that manganese was higher in tubers from upland sediments in 6 out of 15 sediments compared to flooded sediments while the remainder (9 out of 15) were equal. Flooded sediments from IN 3 and ME 3 were the only 2 that resulted in

Table 23

Total Uptake (Concentration × Aboveground Yield) of Heavy Metals by *C. esculentus* Grown in Freshwater Sediments Under Reduced (Flooded) and Oxidized (Upland) Environments

Location*/ Site	Total Uptake, μg pot^{-1}									
	Zn		Cd		Cu		Fe**		Mn**	
	Flooded	Upland	Flooded	Upland	Flooded	Upland	Flooded	Upland	Flooded	Upland
DE 1	552	614	5.4	25.7	28.2	23.4	0.2	0.4	1.3	1.4
2	10939	6560	183.3	340.7	211.2	145.4	7.2	1.3	46.0	35.2
3	953	1313	1.4	10.8	10.6	30.3	0.2	0.2	4.2	3.6
MC 1	6669	15950	138.9	1098.3	171.6	363.6	3.7	2.1	54.1	22.0
2	12450	17340	495.4	2143.7	403.9	617.8	6.2	5.0	65.7	60.3
3	5949	6917	263.6	633.2	280.1	301.5	7.7	7.1	28.9	34.2
IN 1	1384	896	7.6	15.6	42.3	34.4	1.0	0.3	26.9	10.4
2	4324	4742	42.0	194.0	19.1	88.3	2.5	0.7	51.8	70.5
3	7127	4324	27.7	31.7	220.2	65.6	7.5	8.8	29.2	11.3
MW 1	6470	23957	164.0	1180.5	469.7	610.3	6.9	6.2	52.2	63.9
2	4545	3275	20.9	71.3	134.6	112.5	1.3	10.6	30.3	19.8
3	4089	2801	15.6	42.6	113.5	105.5	1.3	1.5	23.1	6.7
ME 1	1146	897	31.3	54.8	310.5	122.5	1.0	0.9	27.0	9.8
2	2676	1934	12.6	34.0	132.1	51.0	1.2	0.7	10.6	13.4
3	1	621	1.2	361.1	16.0	173.4	0.1	1.0	1.5	41.3
$LSD_{0.05}$†	2887		362.3		119.6		5.7		12.4	

Location*/ Site	Total Uptake, μg pot^{-1}									
	As		Hg		Ni		Cr		Pb	
	Flooded	Upland	Flooded	Upland	Flooded	Upland	Flooded	Upland	Flooded	Upland
DE 1	<0.025	<0.025	0.19	0.56	IS††	IS	1.45	2.46	9.7	11.1
2	<0.025	<0.025	9.15	0.40	105.82	17.86	39.36	20.51	539.3	87.0
3	<0.025	<0.025	0.03	0.11	IS	IS	1.34	0.73	5.7	10.5
MC 1	<0.025	<0.025	0.79	4.37	198.36	41.88	323.71	IS	70.6	71.7
2	<0.025	<0.025	9.29	3.57	457.56	264.71	479.99	536.84	241.7	125.4
3	<0.025	<0.025	4.61	1.36	271.50	270.28	359.09	171.75	122.2	70.0
IN 1	<0.025	<0.025	1.32	<0.005	IS	IS	14.36	3.10	26.4	7.8
2	<0.025	<0.025	1.28	0.79	IS	IS	49.19	27.13	63.3	30.3
3	<0.025	1.045	2.81	1.12	12.53	80.96	79.44	17.75	91.6	28.1
MW 1	<0.025	<0.025	0.44	1.17	16.02	62.52	592.75	13.80	138.5	110.9
2	<0.025	<0.025	0.52	0.76	IS	IS	4.05	9.13	39.1	47.0
3	<0.025	<0.025	0.60	0.63	4.74	IS	11.77	24.59	48.0	72.3
ME 1	<0.025	<0.025	<0.005	0.28	IS	IS	21.91	4.68	43.3	40.1
2	<0.025	<0.025	<0.005	0.29	14.69	IS	12.62	12.90	43.9	31.0
3	<0.025	54.432	0.13	0.57	IS	126.68	2.41	21.92	1.7	42.3
$LSD_{0.05}$†	--		4.27		91.8		235.1		131.6	

* Abbreviations are the same as those listed in Figures 5-7.
** Concentrations of Fe and Mn are in mg g^{-1}.
† $LSD_{0.05}$ = Least Significant Difference at $\alpha = 0.05$.
†† IS = Insufficient sample for analysis.

Table 24

Concentration of Heavy Metals in Tuber Tissue of *C. esculentus* Grown in Freshwater Sediments Under Reduced (Flooded) and Oxidized (Upland) Environments

Location*/ Site	Zn Flooded	Zn Upland	Cd Flooded	Cd Upland	Cu Flooded	Cu Upland	Fe Flooded	Fe Upland	Mn Flooded	Mn Upland
	Concentration, $\mu g\ g^{-1}$									
DE 1	46.7	37.8	1.10	1.55	6.36	8.52	1943	162	43.8	12.0
2	39.7	39.4	0.31	1.13	6.58	11.66	1610	91	16.5	6.6
3	69.8	37.5	1.54	0.57	13.04	9.21	1577	67	25.9	5.7
MC 1	54.1	43.0	0.90	2.96	5.74	13.31	1073	54	21.9	3.5
2	55.4	73.1	1.11	4.17	5.43	11.72	1155	542	16.5	20.4
3	55.0	60.5	1.16	2.61	5.46	7.96	1704	375	27.8	30.0
IN 1	50.4	44.5	0.15	0.80	5.00	8.37	2086	423	46.9	13.2
2	55.2	55.5	0.20	1.51	5.80	9.66	3587	359	49.0	24.5
3	150.6	76.0	0.54	0.41	6.61	11.62	9120	237	64.1	9.8
MW 1	45.6	45.4	0.49	2.58	8.98	9.03	1108	101	20.3	10.0
2	42.0	36.0	0.40	0.27	7.13	19.99	1586	83	20.4	6.7
3	39.7	33.5	0.48	0.22	6.50	6.18	1232	79	11.6	4.4
ME 1	34.8	38.6	0.35	0.45	5.05	5.14	598	73	18.8	3.9
2	44.3	50.1	0.25	0.47	7.20	6.90	2273	76	50.7	5.9
3	7.1	33.4	0.53	3.49	3.12	6.90	215	110	21.2	28.4
$LSD_{0.05}$**	17.3		0.71		6.65		1482		19.2	

Location*/ Site	As Flooded	As Upland	Hg Flooded	Hg Upland	Ni Flooded	Ni Upland	Cr Flooded	Cr Upland	Pb Flooded	Pb Upland
	Concentration, $\mu g\ g^{-1}$									
DE 1	0.058	<0.025	0.027	0.008	2.04	7.72	4.15	<0.08	4.61	7.04
2	<0.025	<0.025	0.028	0.005	3.85	2.86	4.88	0.71	2.59	1.60
3	0.176	<0.025	<0.005	<0.005	7.07	2.03	3.43	0.46	2.66	1.00
MC 1	<0.025	<0.025	0.003	0.008	2.35	2.82	1.86	0.63	1.89	0.43
2	0.050	0.008	0.005	0.035	2.44	3.77	1.88	3.71	2.51	2.86
3	<0.025	<0.025	0.004	0.018	3.65	3.08	3.60	1.54	4.34	2.31
IN 1	0.280	0.208	<0.005	0.023	0.81	1.61	3.88	1.29	4.21	2.84
2	0.340	0.317	0.006	0.021	0.98	3.66	4.29	0.43	9.16	9.11
3	0.630	<0.025	0.118	0.018	3.58	3.12	21.41	0.09	32.63	1.77
MW 1	<0.025	<0.025	0.006	0.008	1.01	7.23	3.02	2.43	6.11	13.62
2	<0.025	<0.025	<0.005	0.007	0.11	2.98	0.95	0.82	1.43	4.85
3	<0.025	<0.025	<0.005	0.004	<0.08	1.33	0.12	0.29	0.58	0.87
ME 1	0.150	<0.025	<0.005	0.006	0.40	2.06	0.51	0.39	1.05	3.53
2	1.200	<0.025	<0.005	0.002	1.25	10.02	1.80	0.33	7.23	4.95
3	12.950	1.525	<0.005	0.005	<0.08	4.70	<0.08	0.31	1.56	13.53
$LSD_{0.05}$**	0.322		0.020		5.80		2.97		9.70	

* Abbreviations are the same as those listed in Figures 5-7.
** $LSD_{0.05}$ = Least Significant Difference at $\alpha = 0.05$.

higher arsenic concentration in tubers compared to upland sediments; the rest were equal. Mercury concentration was higher in tubers from plants grown under flooded sediment conditions compared to upland sediment conditions in only 2 out of 15 cases (DE 2 and IN 3); the rest were equal between the two sediment conditions. Nickel concentration in tubers was greater in plants grown in upland sediments compared to flooded sediments in only 2 out of 15 cases (MW 1 and ME 2) while the rest were equal. Chromium concentration in tubers grown in flooded sediment conditions was greater than that from upland sediment conditions in 5 out of 15 cases; the rest (10 out of 15) were equal. Lead concentration in tubers from plants grown in flooded sediments was greater than that from upland sediments in only 1 out of 15 sediments (IN 3); 1 out of 15 had higher tuber lead concentration in plants from upland sediments (ME 3); the remaining 13 out of 15 cases were equal. In summary, upland sediment conditions resulted in increased heavy metal content in tubers for only cadmium. The rest of the heavy metals in tubers were not significantly different between the sediment conditions.

129. Increased heavy metal concentrations in plant tissue of plants grown in upland sediments may result from suppression of plant growth. Such was the case for zinc (MC 2), cadmium (DE 2), copper (MC 1 and MW 2), iron (DE 1 and MW 1), arsenic (IN 3 and ME 3), mercury (DE 2 and IN 3), and chromium (DE 1 and DE 3). All of these tubers had significantly higher concentrations of heavy metal in their tubers when the plants were grown in upland sediments. However, when tuber yield was taken into account, the difference in heavy metal uptake between tubers from upland sediments and flooded sediments was not significant, which indicated that a dilution of heavy metal concentration had occurred.

130. There were several cases where tubers that had higher heavy metal concentrations under one of the sediment conditions were still significant even when total uptake was considered. Cadmium concentration in tubers from upland sediments was significantly higher than that from flooded sediments (Table 25). Total uptake of cadmium from

Table 25

Total Uptake (Concentration × Yield of Tubers) of Heavy Metals by Tuber Tissue of *C. esculentus* Grown Under Reduced (Flooded) and Oxidized (Upland) Environments

Location*/ Site	Total Uptake, $\mu g\ pot^{-1}$ Zn Flooded	Zn Upland	Cd Flooded	Cd Upland	Cu Flooded	Cu Upland	Fe** Flooded	Fe** Upland	Mn** Flooded	Mn** Upland
DE 1	427	366	9.7	11.6	58.9	85.1	17.6	1.7	424	125
2	7653	2775	59.5	76.9	1233.5	828.6	307.7	6.5	3113	460
3	507	454	11.4	6.9	95.9	111.9	11.5	0.8	188	68
MC 1	5407	2911	89.6	199.9	572.6	873.1	106.5	3.6	2168	238
2	8515	7345	171.5	422.4	833.9	1167.0	178.0	51.9	2533	2045
3	4389	5337	95.8	230.6	436.2	704.5	135.0	34.6	2209	2742
IN 1	2475	456	7.6	8.4	245.2	86.7	102.6	3.6	2308	129
2	5283	2249	18.8	61.2	569.2	391.6	347.4	14.7	4761	980
3	2336	2466	9.0	13.3	105.3	378.1	135.1	7.5	947	319
MW 1	4897	4689	51.1	264.0	1084.1	929.2	127.6	10.3	2349	1031
2	2037	1769	19.6	13.2	346.1	981.8	75.4	4.2	978	328
3	2167	2082	26.5	13.3	354.3	385.3	67.8	4.8	633	268
ME 1	1156	2134	11.9	24.6	166.3	285.1	19.2	4.0	607	213
2	561	2205	3.1	19.9	91.1	299.9	28.8	3.4	641	255
3	35	1094	3.2	113.5	14.8	220.6	1.1	3.9	105	948
$LSD_{0.05}$†	469		58.8		509.4		80.3		1297	

	Total Uptake, $\mu g\ pot^{-1}$ As Flooded	As Upland	Hg Flooded	Hg Upland	Ni Flooded	Ni Upland	Cr Flooded	Cr Upland	Pb Flooded	Pb Upland
DE 1	0.50	<0.03	0.300	0.093	18.3	88.2	37.4	<0.1	31.8	81.3
2	<0.03	<0.03	1.709	0.361	735.7	197.7	923.4	49.6	500.6	113.7
3	1.24	<0.03	0.005	0.005	49.5	24.0	25.1	5.3	19.5	12.1
MC 1	<0.03	<0.03	0.255	0.587	234.3	186.9	183.7	41.3	186.6	29.2
2	7.85	0.77	0.775	3.413	375.4	366.5	291.6	367.3	388.7	284.3
3	<0.03	<0.03	0.378	1.693	282.2	282.8	284.0	143.1	342.3	200.0
IN 1	13.59	2.38	0.005	0.243	39.6	17.9	189.7	10.0	206.9	28.3
2	33.62	12.99	0.586	0.845	99.3	146.5	412.5	17.4	893.1	372.8
3	8.69	0.03	1.904	0.591	54.8	99.6	325.9	3.3	509.2	57.9
MW 1	<0.03	<0.03	0.791	0.834	132.8	725.7	349.6	264.6	733.6	1350.2
2	<0.03	<0.03	0.005	0.328	4.8	134.0	47.7	36.5	65.6	219.8
3	<0.03	<0.03	0.005	0.248	<0.1	77.5	6.5	18.3	31.1	54.5
ME 1	4.18	<0.03	0.005	0.322	12.9	110.8	14.3	21.5	34.6	193.7
2	15.18	<0.03	0.005	0.069	15.8	414.4	22.8	13.1	91.4	206.2
3	<63.84	50.68	0.005	0.147	<0.1	196.7	<0.1	13.0	3.9	566.1
$LSD_{0.05}$†	16.35		1.423		91.6		235.0		131.5	

* Abbreviations are the same as those listed in Figures 5-7.

** Concentrations of Fe and Mn are in $mg\ g^{-1}$.

† $LSD_{0.05}$ = Least Significant Difference at α = 0.05.

these upland sediments was still higher than that from flooded sediments. Nickel in tubers from MW 1 and MW 2 and all three sites at ME (upland sediment) was also higher when total uptake was considered. Such was also the case of lead in tubers from ME 3.

Mechanisms of plant
uptake of heavy metals

131. If an element is absorbed passively and translocated freely once inside a plant, its concentration should be highest in the leaves. It should be carried along in the transpiration stream and either be left behind in the leaf as the water is transpired or actually released along with the water. Cadmium, manganese, and zinc appeared to be concentrated more in the aboveground tissue of *C. esculentus* than in the storage organs or tubers. Cadmium appears to be absorbed passively (Cutler and Rains 1974) and translocated freely (Jarvis, Jones, and Hopper 1976). Release of zinc, copper, and lead into the atmosphere from plant leaves has been shown by Beauford, Barber, and Barringer (1975). These same authors, however, could not conclusively show whether the release of heavy metals by this mechanism was associated with water loss due to transpiration or loss of waxlike particles containing the heavy metals. They did, however, find that radioactively labeled zinc absorbed by roots of their plants was translocated to the vicinity of the leaf surface. Since zinc is a required element and acts in several enzymatic reactions associated with plant growth, zinc should be translocated into these locations in the plant.

132. Cadmium is chemically related to zinc. It is possible that cadmium could be transported by the same mechanisms mentioned by Beauford, Barber, and Barringer (1975) since it was shown that cadmium accumulated in the plant tops. The higher level of iron in tubers could be explained by the fact that cadmium caused an actual iron deficiency by inhibiting translocation of iron from roots to tops (Chaney 1970; Lingle, Tiffin, and Brown 1963; Wallace and DeKock 1966).

133. The organic matter content of the sediments used in the present investigation was much greater than those in the above literature. The organic matter of the sediments had not been subjected to aerobic

conditions since the sediments had been dredged from an anaerobic underwater environment. The only aerobic decomposition that occurred was during the air-drying process and during the growth period of the experiment for the upland environment. This aerobic decomposition of the organic matter could have led to greater heavy metal solubility. As discussed in the DTPA extraction section earlier, it appeared that the heavy metals had formed organic complexes that had greater stabilities than the same heavy metal DTPA complexes, at least under anaerobic conditions. Once aerobic decomposition occurred, the heavy metals could have been released from the organic complexes and were available for plant uptake as evidenced by increased heavy metal concentration in the aboveground plant tissue in plants from the upland environment. The importance of organic matter to plant uptake of heavy metals has been shown by numerous researchers (MacLean 1976; Street, Lindsay, and Sabey 1977; Street, Sabey, and Lindsay 1978; Khan and Ryan 1978; Wallace et al. 1977; Shuman and Anderson 1978). In this study, heavy metal concentrations were higher in *C. esculentus* tissue than most reported agricultural plants (especially rice--another semiaquatic plant). One would not have expected such high concentrations of heavy metals in *C. esculentus* considering the high pH and high calcium carbonate contents of the sediments in which the plants were grown. Considerable research has shown availability of heavy metals to decrease as soil pH values increase to 7.0. Consequently, these high plant tissue contents of heavy metals suggest that something else is controlling heavy metal availability to the plants in sediments of high pH and high calcium carbonate contents.

124. Generally, DTPA extracted more heavy metals from upland sediments than from flooded sediments. This suggests that sediment heavy metals were present in the flooded (anaerobic) condition as complex organometallic complexes unavailable for either plant uptake or extraction by DTPA (a good estimator of plant uptake). Upon air drying, aerobic decomposition (oxidation) of organic matter occurred thus decreasing the number of sites on which the heavy metals were complexed and would result in increased plant available heavy metals. Hence,

greater heavy metal uptake would have occurred under the upland condition. It is well known that most heavy metals are rendered less available as the pH increases above 7.0. A high pH and calcium carbonate content in soils limits heavy metal availability to plants, resulting in reduced plant growth and yields. In the present study, however, both high pH and high calcium carbonate content were present as well as high organic matter. Saeed and Fox (1977) found increased zinc solubility in soils with high organic matter when the pH rose above 7.0. They concluded that the increase in zinc solubility was due to dispersion of organic matter that either released complexed zinc or provided chelating agents for added zinc and reduced absorption or precipitation. The findings of Saeed and Fox (1977) support the results of this study that heavy metal availability is predominately controlled by complex formation with organic matter. In addition, manganese has been shown to be very stable in organic complexes compared to copper and iron (copper >> iron > manganese), and since the uptake of manganese under the flooded condition (i.e., before any aerobic decomposition) is not as great as under the aerobic conditions, this indicated that the organometallic manganese complexes formed in the anaerobic flooded state are much more stable (less availability, less plant uptake) than after aerobic decomposition had occurred. Copper and iron, however, chelate so strongly that even after being subjected to aerobic decomposition, their availability for plant uptake or DTPA extractability is not increased.

Relationships of plant heavy metal content to sediment characteristics

135. Results of multiple regression analysis for plant leaf heavy metal concentration are presented in Table 26. The table is arranged such that the predicted plant leaf concentration (for plants grown under a flooded environment $\hat{Y}_{fl}$ or upland environment $\hat{Y}_{up}$) is a function of several measured variables. An indication of the strength of a one-to-one correlation of a particular variable is given by r^2, the simple coefficient of determination. The test for significance of adding that variable to the equation once the other variables are in the equation is given by partial-F. The portion of variation about the estimated mean

Table 26

Prediction Equations for Heavy Metal Leaf Concentrations in *C. esculentus* Grown Under Reduced (Flooded-fl) and Oxidized (Upland-up) Environments

Prediction Equation	Simple Coefficient of Determination, r^2	Partial-F	Coefficient of Determination, R^2
	Plant Leaf Concentration, Zn		
$\hat{Y}_{fl}$ = 137.6 − 0.099 × DTPAWFE	0.386	27.44	
− 0.159 × DTPAWMN	0.345	16.43	
+ 1.385 × SEDCLAY	0.139	9.03	
+ 1.017 × HNO3CD	0.001	8.87	0.894
$\hat{Y}_{up}$ = 149.8 + 54.65 × DTPAWCD	0.298	36.12	
+ 0.137 × DTPADZN	0.114	27.00	
− 304.0 × DTPAWOP4	0.016	13.38	
− 12.01 × DTPADIMN	0.029	6.28	0.868
	Plant Leaf Concentration, Cd		
$\hat{Y}_{fl}$ = 0.3638 + 0.0837 × DTPADCD	0.824	144.86	
+ 0.1590 × DTPAWCD	0.025	13.91	
− 0.0063 × DTPAWIMN	0.000	8.17	0.931
$\hat{Y}_{up}$ = −3.742 + 3.050 × DTPAWCD	0.190	39.52	
− 0.155 × DTPAWIMN	0.001	29.25	
+ 0.764 × INSTWIMN	0.213	17.95	
+ 30.08 × DTPADOP4	0.293	8.27	0.884

(Continued)

Table 26 (Continued)

Prediction Equation	Simple Coefficient of Determination, r^2	Partial-F	Coefficient of Determination, R^2
	Plant Leaf Concentration, Cu		
$\hat{Y}_{f1}$ = 4.218 + 0.2976 × INSTWMN	0.616	42.07	
− 0.0047 × DTPADFE	0.030	9.43	0.785
$\hat{Y}_{up}$ = 3.949 + 0.9329 × DTPAWCD	0.165	23.04	
− 0.4617 × DTPADIMN	0.000	21.14	
+ 7.948 × DTPADOP4	0.233	14.12	
− 40.69 × INSTWCU	0.166	11.83	0.838
	Plant Leaf Concentration, Fe		
$\hat{Y}_{f1}$ = 27.38 + 0.0039 × HNO3ZN	0.776	92.89	
+ 0.5880 × INSTWFE	0.026	12.08	0.889
$\hat{Y}_{up}$ = 3.191 + 0.0080 × HNO3ZN	0.513	46.20	
+ 0.0008 × HNO3FE	0.473	41.87	0.892
	Plant Leaf Concentration, Ni		
$\hat{Y}_{f1}$ = −0.0987 + 0.0970 × DTPADCD	0.912	36.28	
− 0.0063 × DTPAWNI	0.497	0.13	
+ 1.040 × INSTWNI	0.335	0.11	0.912
$\hat{Y}_{up}$ = −2.040 + 7.863 × DTPADOP4	0.745	9.90	
+ 0.1112 × INSTWIMN	0.533	8.68	
+ 19.78 × DTPADCDZ	0.116	6.10	0.869

(Continued)

Table 26 (Concluded)

Prediction Equation	Simple Coefficient of Determination, r^2	Partial-F	Coefficient of Determination, R^2
	Plant Leaf Concentration, Cr		
$\hat{Y}_{f1}$ = 0.0563 + 0.1234 × DTPADCD	0.372	16.99	
+ 0.0091 × DTPADPB	0.398	15.14	
− 0.0470 × DTPADNI	0.180	3.28	0.792
$\hat{Y}_{up}$ = 0.2554 + 0.1503 × DTPADCD	0.646	34.14	
− 5.517 × INSTWNI	0.046	5.75	0.768
	Plant Leaf Concentration, Pb		
$\hat{Y}_{f1}$ = −0.1596 + 0.1294 × DTPADIMN	0.432	31.49	
+ 0.0619 × SEDCARN3	0.000	11.20	
+ 0.0195 × DTPADCD	0.066	7.91	0.760
$\hat{Y}_{up}$ = 0.9595 + 0.0439 × DTPADIMN	0.471	34.34	
+ 0.0106 × SED15BAR	0.082	12.43	
− 0.9543 × DTPADOP4	0.128	11.84	
+ 0.00001 × SEDNH3N	0.110	3.94	0.869

(Sheet 3 of 3)

(in this case, plant leaf heavy metal concentration) that is explained by the variables of the equation is given by R^2, the multiple coefficient of determination.

136. An illustration of how the prediction equation was developed is best described by using an example (Table 26). Plant leaf zinc, $\hat{Y}_{f1}$, would be predicted by a combination of DTPAWFE, DTPAWMN, SEDCLAY, and HNO3CD, and these would explain 89.4 percent of the variability of plant leaf zinc. DTPAWFE contributed most to the overall prediction equation (as given by a partial-F of 27.44). DTPAWFE by itself was negatively correlated with plant zinc and explained only 38.6 percent $(-r)^2$ of the variability in plant zinc. DTPAWMN was the next strongest variable explaining 34.5 percent of the variability in plant zinc. SEDCLAY was third and explained only 13.9 percent of zinc variability. HNO3CD was least and explained 0.1 percent of zinc variability in the plant leaf. The first two variables in the prediction equation were DTPA extractable and together accounted for a substantial portion of plant zinc. Plant leaf zinc in plants grown under upland conditions would be predicted by a combination of four DTPA extracts under both wet and dry conditions and would account for 86.8 percent of the variability in plant zinc. In fact, plant leaf concentration of the other heavy metals studied (except iron--flooded and upland, and manganese--flooded) was predicted by a combination of DTPA extractable metals. Plant concentration of heavy metals did not seem to be related to sediment nitrogen or phosphorus nor was a DTPA flooded (DTPAW) extract always associated with plants grown in flooded sediments. Rather, both DTPAW and DTPA air dried (DTPAD) were related to plant concentration of heavy metals.

137. A combination of DTPAW and DTPAD extractable heavy metals also predicted total plant uptake of heavy metals. Again, total plant uptake of iron and manganese was different from the other heavy metals in that extractable heavy metals appeared in the prediction equations. The iron to manganese ratio in both DTPAW and DTPAD extracts appeared several times in the prediction equations, which indicated that iron and manganese were affecting plant content and uptake of the other

heavy metals. Very few phosphorus terms appeared in the prediction equations and no nitrogen terms appeared. This was unexpected, as total plant uptake should have been influenced by plant growth (i.e., the dilution effect) but was not. Apparently, plant growth was affected by heavy metals more so than by nitrogen or phosphorus.

138. Plant available heavy metals appear to be related somewhere in between DTPAW and DTPAD extractable heavy metals. Not all of the heavy metals extractable by DTPA under dry oxidized conditions are plant available. If they were, plant levels of heavy metals should have been higher as predicted by the high DTPAD heavy metal values nor are plant heavy metals as low as DTPAW would predict. If they were, then plant levels of heavy metals should have been lower.

139. The results of the prediction work indicated that pH and calcium carbonate were not associated with heavy metal uptake; therefore, some other mechanism(s) was controlling plant availability of heavy metals. The heavy metals in the interstitial water extracts were not completely associated with plant uptake of the heavy metals either. Oxidation-reduction related mechanisms were probably involved in controlling plant availability of heavy metals. Iron and manganese in DTPA extracts appeared several times in the prediction equations. Heavy metals released from desorption onto iron and manganese oxides/hydroxides as oxidation occurred during the drying process appeared to be related to plant uptake of heavy metals only in the respect that, as the organic matter cementing together the oxide/hydroxide particles was removed by decomposition processes, some manganese compounds became more soluble under oxidized conditions. Any adsorbed heavy metals associated with those compounds could have become available for plant uptake. Heavy metals extracted by DTPA were more closely related with plant uptake of heavy metals than with the other sediment chemical or physical variables. The possibility that the organic fraction of the sediments controlled heavy metal availability can be inferred because DTPA extraction was closely associated with the organic fraction of sediments as mentioned earlier. It seemed as though the organic fraction contained many compounds capable of complexing the heavy metals and strongly affected

plant availability of heavy metals. The fact that organic matter itself did not appear in the prediction equations was probably a result of the organic fraction being so complex. One can assume that only a portion of the organic fraction and not the total fraction was associated with controlling plant availability of heavy metals. The determination of organic matter was not, however, sensitive enough to isolate the reactive fractions.

140. It should be pointed out that these relationships are not to be considered definitive. One limitation on the equations is due to the fact that a large number of parameters were determined on a relatively small number of plant and sediment samples.

141. Rencher and Pun (1980) have shown that, when using stepwise regression, as much as a 50 percent inflation in R^2 can occur due to combinations of data that occur from random or chance correlation. In cases where there are more predictor variables than observations (as there was in this study, i.e., 15 sediment sites and approximately 80 variables), more than half of the R^2 values can be greater than 0.90; hence, the results must be interpreted with caution.

142. Another possible weakness in these relationships is the presence of extreme values that could result in higher linear relationships.

143. The above are some of the reasons that prediction of heavy metal content of plants is so complex and difficult. The reader should be aware of the possible influences of those limitations when developing relationships for heavy metal contents of freshwater marsh plants. Any relationships developed need to be verified through further experiments. Consequently, the equations in Tables 26 and 27 should be verified before widespread application.

Saltwater Experiment

Sediment physical characteristics

144. Moisture content. The moisture content of the saltwater sediments at three soil moisture tensions is presented in Table 28. As

Table 27

Prediction Equations for Total Plant Uptake of Heavy Metals by *C. esculentus* Grown Under Reduced (Flooded-fl) and Oxidized (Upland-up) Environments

Prediction Equation	Simple Coefficient of Determination, r^2	Partial-F	Coefficient of Determination, R^2
	Total Plant Uptake, Zn		
$\hat{Y}_{fl}$ = -144.2 + 5.802 × DTPAWZN	0.469	26.75	
+ 39390 × DTPAWOP4	0.276	26.60	
- 36.11 × DTPAWMN	0.204	18.65	
- 85.85 × DTPAWIMN	0.349	5.79	0.908
$\hat{Y}_{up}$ = 4601 + 3849 × DTPAWCD	0.367	44.84	
+ 971 × INSTWIMN	0.180	32.42	
- 139 × HNO3IMN	0.001	16.01	0.848
	Total Plant Uptake, Cd		
$\hat{Y}_{fl}$ = -122.5 + 18.53 × DTPADCD	0.671	124.65	
+ 28.85 × DTPADIMN	0.085	40.55	
+ 857.2 × INSTWNI	0.201	24.87	0.941
$\hat{Y}_{up}$ = -454.5 + 83.13 × DTPADCD	0.389	49.85	
- 5616 × INSTWNI	0.038	21.20	
+ 122.6 × DTPADIMN	0.019	14.55	0.836

(Continued)

(Sheet 1 of 4)

Table 27 (Continued)

Prediction Equation	Simple Coefficient of Determination, r^2	Partial-F	Coefficient of Determination, R^2
	Total Plant Uptake, Cu		
$\hat{Y}_{fl}$ = 96.16 − 1.997 × DTPADMN	0.239	33.82	
+ 1269 × DTPADOP4	0.177	31.05	
+ 1.028 × DTPAWPB	0.259	20.07	
− 2.277 × DTPAWIMN	0.049	10.58	0.882
$\hat{Y}_{up}$ = 190.5 + 27.01 × INSTWIMN	0.237	63.75	
+ 1.761 × DTPAWPB	0.286	52.36	
− 4.542 × HNO3IMN	0.040	45.33	0.919
	Total Plant Uptake, Fe		
$\hat{Y}_{fl}$ = −245.7 + 376.4 × INSTWIMN	0.287	33.41	
+ 0.2318 × HNO3ZN	0.229	25.74	
+ 1115 × DTPAWCD	0.176	23.00	0.860
$\hat{Y}_{up}$ = −1980 + 0.3426 × HNO3ZN	0.473	33.89	
+ 230.1 × INSTWIMN	0.229	4.75	
+11125 × DTPADOP4	0.110	2.47	0.811

(Continued)

(Sheet 2 of 4)

Table 27 (Continued)

Prediction Equation	Simple Coefficient of Determination, r^2	Partial-F	Coefficient of Determination, R^2
	Total Plant Uptake, Mn		
$\hat{Y}_{fl}$ = 18512 + 11255 × DTPAWCD	0.314	40.92	
+ 87.88 × DTPADZN	0.150	31.69	0.843
− 19.26 × HNO3OP4	0.052	19.66	
$\hat{Y}_{up}$ = 4614 + 6.094 × SEDOILGR	0.272	26.15	
− 677.9 × HNO3IMN	0.001	17.24	
+ 115988 × DTPADOP4	0.206	9.56	
+ 5574 × DTPAWCD	0.076	7.03	0.948
	Total Plant Uptake, Ni		
$\hat{Y}_{fl}$ = −33.31 + 11.64 × DTPADCD	0.692	36.80	0.843
+ 0.4592 × DTPAWZN	0.151	5.69	
$\hat{Y}_{up}$ = −79.40 + 7.259 × DTPADCD	0.856	85.[illegible]5	0.948
+ 391.8 × DTPADOP4	0.576	21.17	

(Continued)

(Sheet 3 of 4)

AD-A112 279 ARMY ENGINEER WATERWAYS EXPERIMENT STATION VICKSBURG--ETC F/G 13/2
INFLUENCE OF DISPOSAL ENVIRONMENT ON AVAILABILITY AND PLANT UPT--ETC(U)
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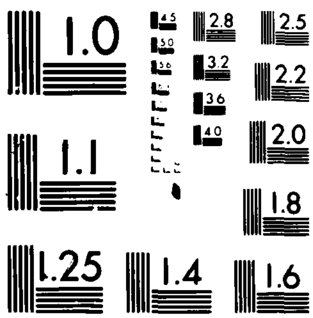

MICROCOPY RESOLUTION TEST CHART
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Table 27 (Concluded)

Prediction Equation	Simple Coefficient of Determination, r^2	Partial-F	Coefficient of Determination, R^2
	Total Plant Uptake, Cr		
$\hat{Y}_{fl} = -28.86 + 23.57 \times DTPADCD$	0.407	59.86	
$+ 1.773 \times DTPAWPB$	0.326	43.52	
$- 5.769 \times DTPAWNI$	0.141	19.65	0.910
$\hat{Y}_{up} = -40.14 + 19.38 \times DTPADCD$	0.607	38.03	
$- 897.9 \times INSTWNI$	0.031	11.31	
$+ 9.828 \times DTPAWCU$	0.068	3.75	0.814
	Total Plant Uptake, Pb		
$\hat{Y}_{fl} = -144.8 + 35.95 \times DTPADIMN$	0.729	66.82	
$+ 8.486 \times INSTWIMN$	0.075	14.63	
$+ 0.3578 \times DTPAWPB$	0.331	3.68	0.920
$\hat{Y}_{up} = 23.46 + 23.17 \times DTPAWCD$	0.341	27.57	
$+ 4.403 \times DTPADCD$	0.261	22.05	
$- 1.190 \times DTPAWNI$	0.189	8.39	0.810

(Sheet 4 of 4)

Table 28

Selected Physical Characteristics of the Saltwater Sediments Used in the Study

Location*/	Moisture Content, %			Plant Available	Particle Size, %			
Site	1/3 Bar	1 Bar	15 Bar	Moisture, %	Sand	Silt	Clay	Texture**
BRH	64.5	39.5	21.4	43.1	36.7	51.2	12.1	Silt loam
JNC	73.9	55.9	36.1	37.8	17.5	74.1	8.4	Silt loam
COL	51.8	38.9	23.8	28.0	21.7	71.2	7.1	Silt loam
BER	43.0	36.3	37.0	6.0	45.9	46.6	7.5	Loam
NWB	58.3	46.9	29.4	28.9	10.4	83.3	6.3	Silt
CC 1	73.6	64.2	35.8	37.8	1.7	85.8	12.5	Silt
2	69.8	62.7	40.6	29.2	22.1	67.0	10.9	Silt loam
3	54.3	48.3	30.8	23.5	21.3	67.0	11.7	Silt loam
OH 1	55.7	46.6	29.0	26.7	4.2	79.5	16.3	Silt loam
2	51.2	39.5	28.8	22.4	12.5	70.8	16.7	Silt loam
3	20.8	15.1	9.0	11.8	65.4	18.3	16.3	Sandy loam
SE 1	45.4	29.7	13.1	32.3	35.9	52.0	12.1	Silt loam
2	46.1	29.6	13.3	32.8	38.0	49.9	12.1	Silt loam
3	57.9	37.2	21.8	36.1	17.5	75.8	6.7	Silt loam

* Abbreviations correspond to those listed in Figures 2-4.
** Based on U. S. Department of Agriculture 7th Approximation Classification Scheme.

mentioned previously, the moisture content of a sediment between 1/3 and 15 bars tension indicates plant available moisture. The saltwater sediments had plant available moistures similar to those of the freshwater sediments (i.e., the sandy sediments had lower plant available moisture than the finer textured sediments).

145. Particle-size distribution. Particle-size distribution (texture) of the saltwater sediments was predominantely fine-grain silt loam (Table 28).

146. The fine-grain fraction of a sediment is closely associated with the relative abundance and chemistry of heavy metals. The association of the fine-grain fraction of a sediment and heavy metal chemistry was discussed in the freshwater section and is also applicable to the saltwater sediments.

Sediment chemical characteristics

147. Some of the general chemical characteristics of the saltwater sediments are given in Table 29. Since the importance of these general chemical characteristics to availability and plant uptake of heavy metals has been discussed in detail in relation to the freshwater sediments, only a brief discussion will be given here for saltwater sediments.

148. Organic matter. Organic matter in the saltwater sediments ranged from a low of 2.8 percent (OH 3) to a high of 26.7 percent (BER). Sediments from Bridgeport, Conn., and Baltimore, Md., had higher organic matter contents than did sediments from the other saltwater locations. Organic matter content of the saltwater sediments was generally within the same range as the freshwater sediments (2.7 to 29.5 percent).

149. Calcium carbonate equivalent - sediment pH. The CCE of the saltwater sediments ranged from a low of 0.0 percent to a high of 7.7 percent. The sediments were slightly calcareous. [illegible] of the sediments was alkaline (pH >7.00) under flooded conditions. However, when the sediments were subjected to air drying, certain sediments had an acidic pH (BRH, JNC, COL, BER, and NWB). A combination of high organic matter and low CCE decreased the pH of freshwater sediments upon air drying and resulted in increased availability and plant uptake of certain

Table 29

Selected Chemical Parameters of the Saltwater Sediments

Location*/ Site	Organic Matter %	Salinity ppt	$CaCO_3$ Equivalent %	pH Flooded**	pH Upland†	Total P $mg\ g^{-1}$	TKN $mg\ g^{-1}$	Oil & Grease $mg\ g^{-1}$	Total S $mg\ g^{-1}$	Na $mg\ g^{-1}$	K $mg\ g^{-1}$
BRH	16.4	---	0.4	---	7.0	1.35	4.02	27.6	14.8	13.3	1.6
JNC	14.2	26.0	1.3	7.3	6.8	1.03	3.62	11.0	14.3	13.6	2.9
COL	12.0	18.0	0.4	7.1	6.5	1.11	3.18	11.4	13.2	4.5	0.9
BER	26.7	11.7	0.3	7.2	5.5	---	5.32	97.5	28.1	6.4	0.7
NWB	11.9	14.0	0.1	7.2	6.3	1.30	3.20	50.4	17.9	4.9	1.4
CC 1	8.9	29.7	7.4	7.5	8.1	0.51	1.41	0.3	5.0	21.0	4.5
2	9.0	30.0	7.7	7.5	8.1	0.36	1.39	0.6	4.5	23.5	4.3
3	8.3	29.0	6.2	7.5	7.9	0.34	1.50	3.2	3.3	18.6	4.3
OH 1	8.3	34.0	0.4	7.3	7.8	1.18	1.82	1.9	3.1	13.1	3.0
2	8.0	33.3	0.4	7.4	8.0	1.08	1.86	3.8	5.4	11.4	2.6
3	2.8	36.3	0.2	7.3	8.0	0.36	0.78	1.7	2.3	4.2	1.2
SE 1	6.6	32.3	0.2	7.2	7.7	0.87	1.13	4.0	5.0	7.7	1.6
2	6.2	32.7	0.2	7.3	7.4	0.73	1.15	2.7	3.8	7.7	1.5
3	8.5	32.0	0.0	7.1	7.3	---	1.95	10.5	9.4	10.5	.9
CV††	7.0	3.3	30.1	0.9	0.2	12.3	4.20	33.4	25.6	8.7	9.1

* Abbreviations correspond to those listed in Figures 2-4.
** Flooded pH is pH of the initial interstitial water.
† Upland pH is pH of a 1:2 sediment to solution suspension using air-dried sediment.
†† CV = coefficient of variation (%).

heavy metals. A similar effect would be expected in the saltwater sediments BRH, JNC, COL, BER, and NWB.

150. Total sulfur. The total sulfur content of the saltwater sediments ranged from 2.3 to 28.1 mg g^{-1} (Table 29). These values were greater than those of the freshwater sediments and were somewhat higher than those normally found in most agricultural soils.

151. A high sulfur content in a sediment in combination with a high organic matter content and a low calcium carbonate equivalent can result in a lowering of sediment pH when oxidization occurs during and after air drying. If there are little or no alkaline carbonates present to neutralize the acid formed during the oxidation process, then the pH would decrease and an acidic condition similar to the "Kattiklei" condition in Holland would occur (Fleming and Alexander 1961). The resultant decrease in saltwater sediment pH upon air drying can be expected to result in enhanced availability and plant uptake of heavy metals, especially for cadmium and zinc.

152. Oil and grease. The O&G concentration of the saltwater sediments ranged from 0.3 mg g^{-1} to as high as 97.5 mg g^{-1} (Table 29). Sediments from Bridgeport, Conn. (BRH and JNC), and Baltimore, Md. (COL, BER, NWB), contained the greatest O&G concentration. Except for these sediments, the O&G concentration in the saltwater sediments was approximately the same as that of the freshwater sediments reported in the literature (Yu et al. 1978, Engineering-Science, Inc. 1977; Gambrell, Khalid, and Patrick 1978).

153. Total P and TKN. Total P in the saltwater sediments ranged from a low of 0.34 mg g^{-1} to 1.35 mg g^{-1} (Table 29). The level of total P was not as high as that found in some of the freshwater sediments but was similar to those normally found in soils (Buckman and Brady 1969; Jackson 1964).

154. The TKN ranged from a low of 0.78 mg g^{-1} to a high of 5.32 mg g^{-1}. These values of TKN were similar to those normally found in soils and freshwater and other saltwater sediments (Brannon et al. 1976a, 1976b; Brannon, Plumb, and Smith 1978; Gambrell, Khalid, and Patrick 1978; Yu et al. 1978).

155. Sodium and potassium. The sodium content of the sediments ranged from a low of 4.2 mg g^{-1} to a high of 23.5 mg g^{-1}. The level of sodium in the sediments is well above the range of that normally found in soils or freshwater sediments and reflects the saline environment of their origin.

156. The potassium content of the sediments ranged from 0.7 mg g^{-1} to as high as 4.5 mg g^{-1}. The potassium level of the sediments is also higher than that normally found in soils. The increased potassium content also reflects the saline origin.

157. Salinity. The salinity of the original reduced sediment IW ranged from 11.7 to 36.3 ppt, which is indicative of sediments from saline environments. Air drying these sediments resulted in IW salinities of greater than 90 ppt. Available literature indicated that no saltwater plants will survive in saline environments greater than 70 to 80 ppt (Adams 1963).

158. Redox potential. The redox potential of the flooded saltwater sediments was initially less than -200 mV, depicting intensely reduced conditions (Table 30). These already low redox potentials decreased even more to near -400 mV after 4 weeks of plant growth, then increased slightly to near -300 mV at the end of the experiment some 18 weeks later. The extremely reduced environment would result in heavy metals being immobilized as sulfides (Gambrell, Khalid, and Patrick 1978). One would expect, therefore, that not much plant uptake of heavy metal would occur as long as the extremely reducing environment prevailed.

Plant growth

159. *Spartina alterniflora.* Growth of *S. alterniflora* on the flooded saltwater sediments is depicted in Figures 21-25. Differences in plant growth occurred mainly between geographic locations more so than between sites within each location, with the exception of plant growth on JNC and BRH sediments. Plant growth between sites on sediments from the four other locations appeared similar. Overall plant growth seemed to be the best on sediments from Baltimore. The least plant growth appeared to be on sediments from Corpus Christi.

160. *Distichlis spicata.* General growth patterns of *D. spicata*

Table 30

Oxidation-Reduction Potential of the Saltwater Sediments

During the Growth of *S. alterniflora* and *D. spicata*

Location*/ Site	Oxidation-Reduction Potential, mV — Weeks After Planting: 0		2		4		18	
	*Spart.***	*Dist.*†	*Spart.*	*Dist.*	*Spart.*	*Dist.*	*Spart.*	*Dist.*
BRH	-458††	-288	-348	-278	-358	-378	-358	-268
JNC	-438	-478	-478	-518	-478	-558	-518	-438
COL	-248	-268	-318	-308	-318	-518	-218	-398
BER	-288	-408	-208	-468	-378	-438	-308	-338
NWB	-168	-148	-328	-288	-398	-338	-358	-288
CC 1	-108	-238	-288	-238	+ 32	-358	-182	-338
2	-448	-178	-428	-228	-478	-238	-398	-198
3	+ 2	- 63	-348	-288	-398	-258	-298	-238
OH 1	-308	-118	-388	-308	-408	-328	-363	-278
2	-193	-293	-203	-373	-408	-418	-363	-358
3	-231	-258	-328	-318	-338	-338	-328	-328
SE 1	-178	-168	-278	-318	-338	-338	-328	-338
2	-178	-148	-298	-288	-398	-278	-388	-278
3	-248	-248	-308	-288	-368	-418	-438	-338

* Abbreviations correspond to those listed in Figures 2-4.

** *Spart.* = *S. alterniflora*.

† *Dist.* = *D. spicata*.

†† All values have been corrected for the half-cell potential of a saturated potassium chloride calomel electrode (+242 mV) and presented at the pH of the sediment.

Figure 21. Growth of *S. alterniflora* (above) and *D. spicata* (below) on sediments from two sites at Bridgeport Harbor (BRH and JNC), Conn.

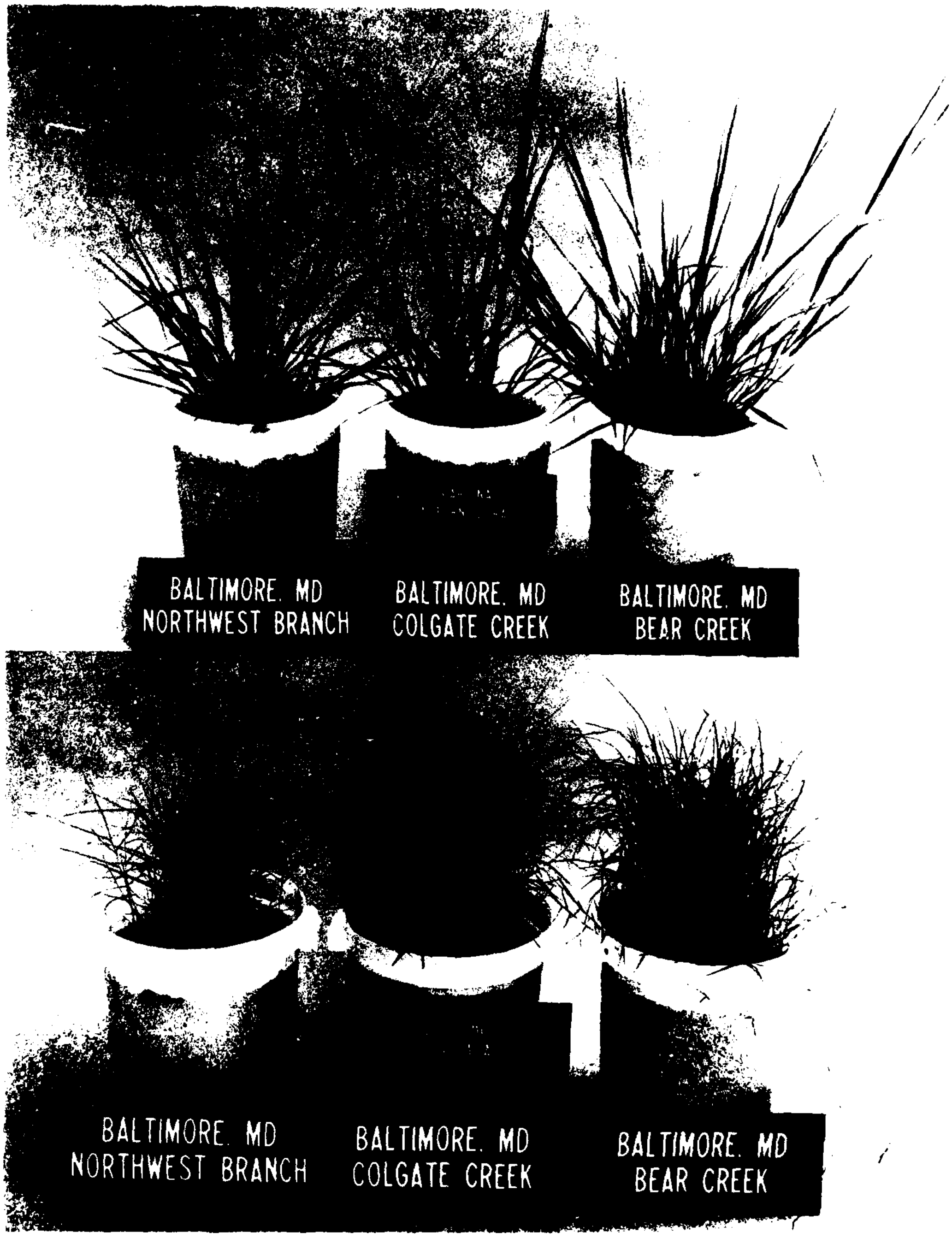

Figure 22. Growth of *S. alterniflora* and *D. spicata* on sediments from three sites in Baltimore Harbor (COL, BER, and NWB), Md.

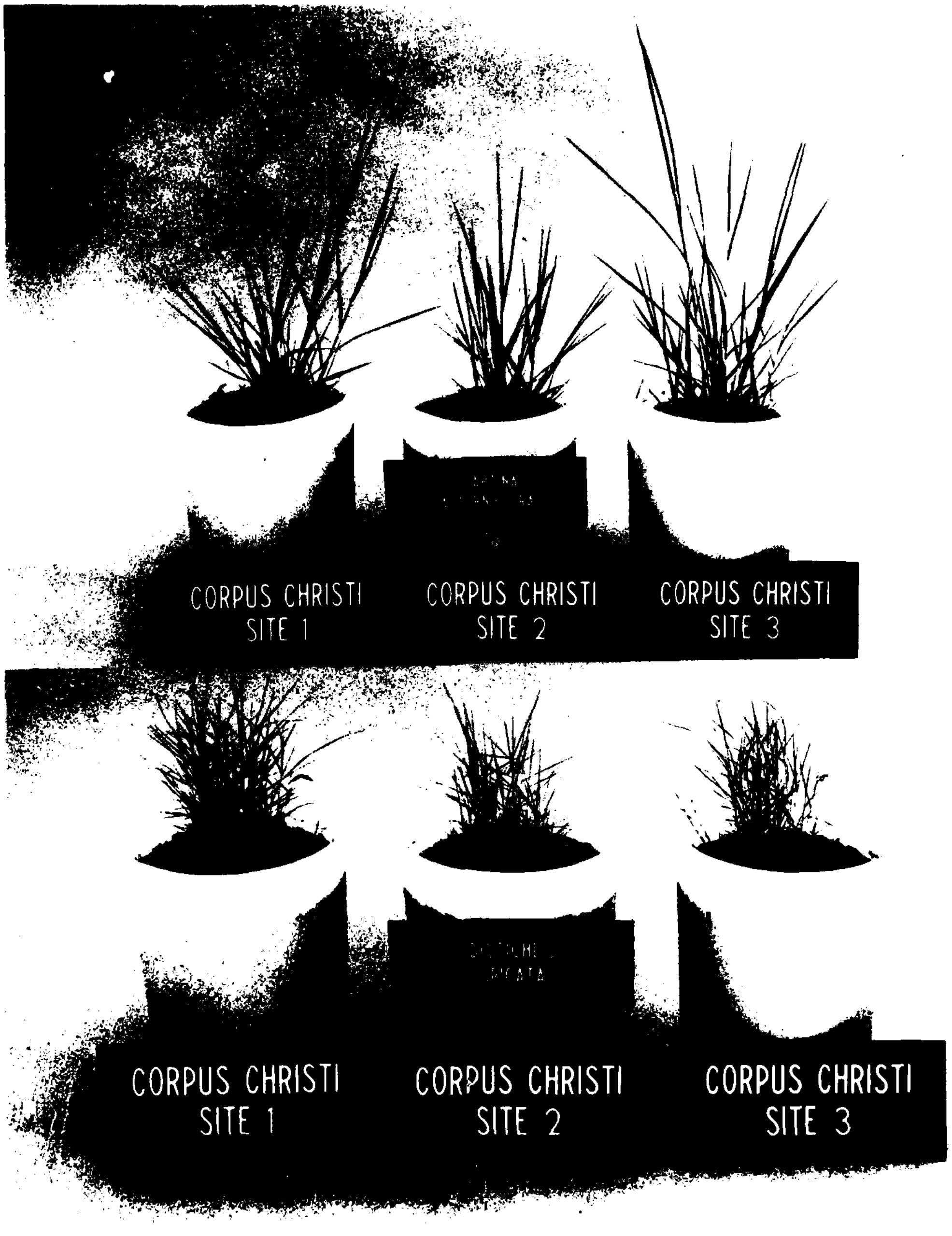

Figure 23. Growth of *S. alterniflora* and *D. spicata* on sediments from three sites in Corpus Christi Harbor (CC), Tex.

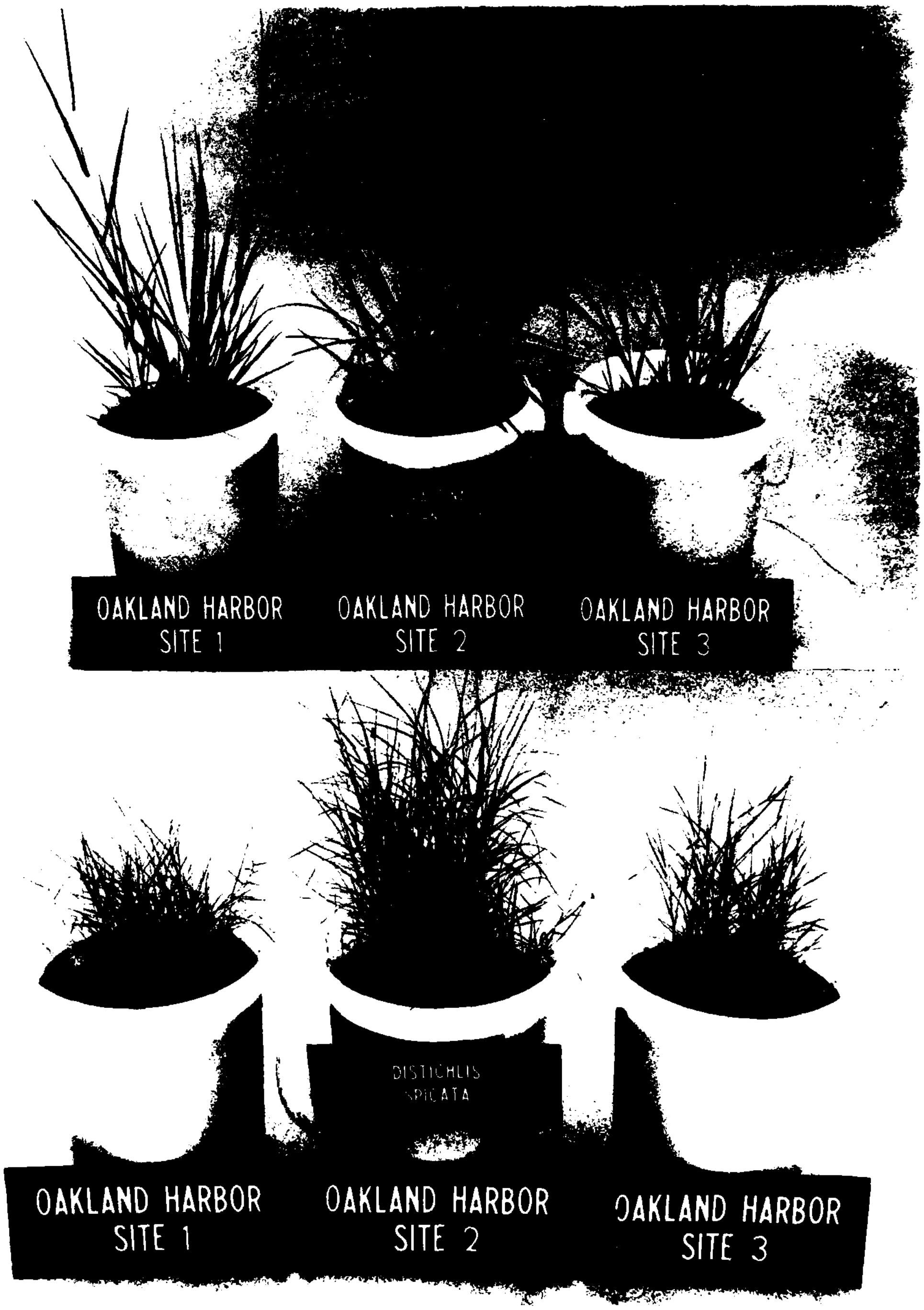

Figure 24. Growth of *S. alterniflora* and *D. spicata* on sediments from three sites in Oakland Inner Harbor (OH), Calif.

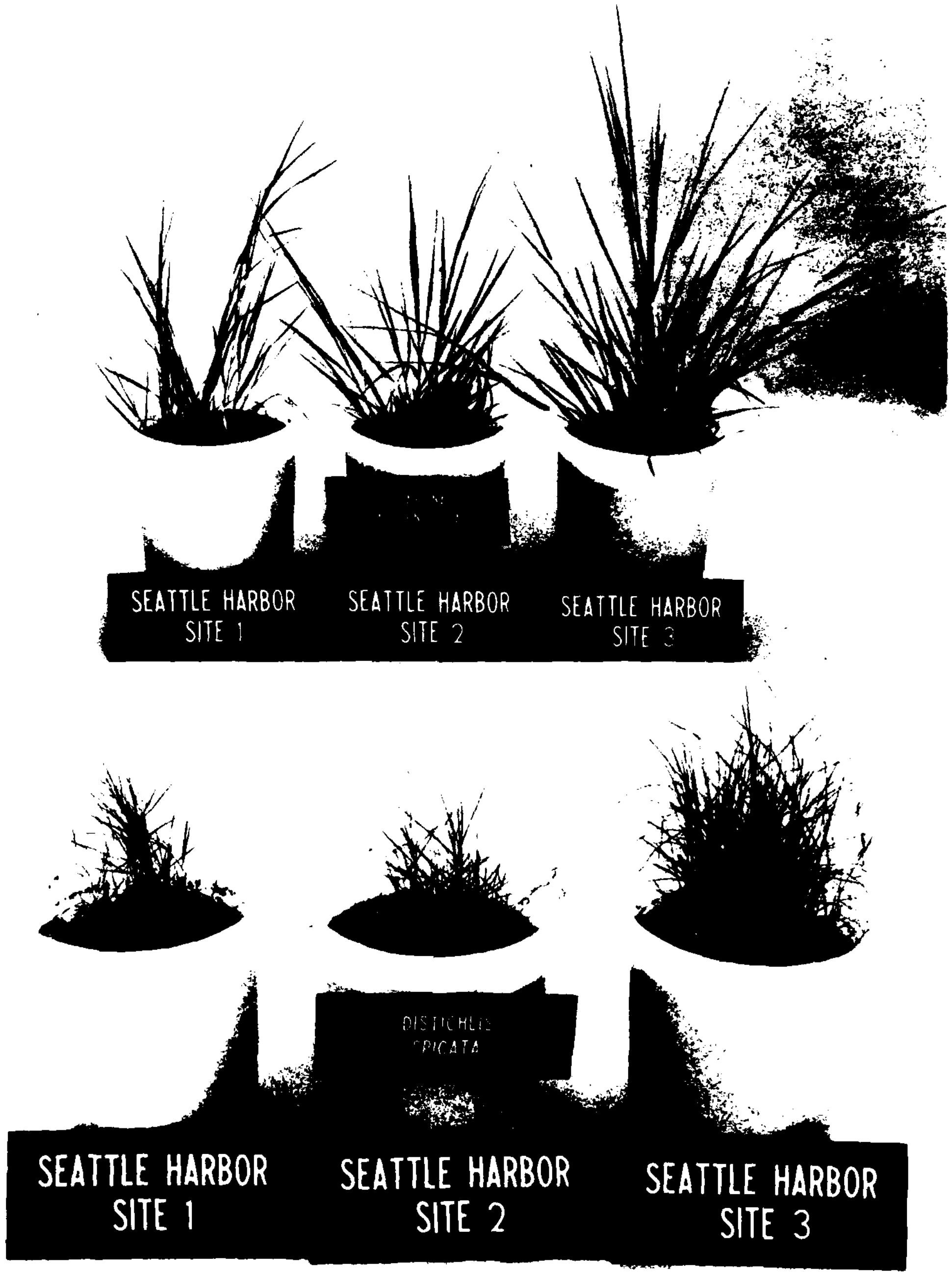

Figure 25. Growth of *S. alterniflora* and *D. spicata* on sediments from three sites in the Duwamish Waterway, Seattle (SE), Wash.

on the saltwater sediments paralleled those of *S. alterniflora.*

Plant yield

161. Aboveground-*S. alterniflora.* Yield data for *S. alterniflora* grown on the flooded saltwater sediments are presented in Table 31. Yield has been separated into three components: live, dead, and the sum of live and dead. Plants grown on sediment from BER had the greatest total yield (53.8 g pot^{-1}) while those grown in sediment from CC 2 had the lowest total yield (6.0 g pot^{-1}).

162. Belowground-*S. alterniflora.* Belowground yield for *S. alterniflora* was composed of both root and rhizome tissue. The greatest belowground yield occurred on sediments from BER (85.9 g pot^{-1}). Plants grown on sediments from CC 2 had the smallest belowground yield (15.7 g pot^{-1}). Belowground yield of *S. alterniflora* was consistently greater by almost 2:1 than total aboveground yield for plants grown on all the saltwater sediments.

163. Aboveground-*D. spicata.* Yield data for *D. spicata* are also presented in Table 31. Plants grown on sediments from BER also had the greatest total aboveground yield (61.1 g pot^{-1}). Plants grown on sediments from CC 2 resulted in the smallest total aboveground yields (4.4 g pot^{-1}).

164. Belowground-*D. spicata.* Plants grown on sediments from BER also had the greatest belowground yield of *D. spicata* (61.2 g pot^{-1}). Plants grown on sediments from CC 2 had the smallest belowground yield (13.0 g pot^{-1}). As with *S. alterniflora*, the belowground yield of *D. spicata* was consistently greater than aboveground yield.

165. Differences in plant growth and yield of both *S. alterniflora* and *D. spicata* on these sediments have been reported to be related exclusively to sediment fertility (Smart and Barko 1980). Smart and Barko (1980) inferred that plants of both species on all sediments were nitrogen limited. Consequently, under low nutrient conditions, belowground tissue production is favored more so than aboveground tissue production (Smart and Barko 1980; Broome, Woodhouse, and Seneca 1975; Barko and Smart 1979; Valiela, Teal, and Persson 1976). However, another explanation of increased belowground tissue production

Table 31

Yield of the Saltwater Marsh Plants *S. alterniflora* and *D. spicata*

Location*/ Site	Aboveground Yield, g pot^{-1} Live		Dead		Total Aboveground		Belowground Yield, g pot^{-1}	
	*Spart.***	*Dist.*†	*Spart.*	*Dist.*	*Spart.*	*Dist.*	*Spart.*	*Dist.*
BRH	15.9	10.6	2.9	--	18.8	10.6	28.8	11.9
JNC	16.6	21.9	6.2	--	22.8	21.9	40.0	34.1
COL	18.9	35.2	9.9	--	28.8	35.2	52.1	57.0
BER	33.0	61.1	20.8	--	53.8	61.1	85.9	61.2
NWB	11.2	11.7	4.2	--	15.4	11.7	31.4	26.7
CC 1	5.5	6.9	1.5	--	7.0	6.9	18.7	17.1
2	4.9	4.4	1.1	--	6.0	4.4	15.7	13.0
3	9.9	11.8	4.3	--	14.2	11.8	30.5	19.0
OH 1	11.3	10.6	4.3	--	15.6	10.6	34.6	20.3
2	19.2	22.8	13.1	--	32.3	22.8	59.7	40.4
3	6.8	9.1	3.4	--	10.3	9.1	23.2	23.7
SE 1	9.7	8.3	3.8	--	13.6	8.3	26.9	15.8
2	6.0	7.3	4.7	--	10.7	7.3	20.8	12.9
3	26.7	32.3	15.3	--	42.0	32.2	63.7	42.4
$LSD_{0.05}$††	4.3		--		4.6		9.8	

* Abbreviations correspond to those listed in Figures 2-4.
** *Spart.* = *S. alterniflora*.
† *Dist.* = *D. spicata*.
†† $LSD_{0.05}$ = Least Significant Difference at $\alpha = 0.05$.

could have been a result of diminishing photoperiod. A diminishing photoperiod has been shown to result in increased belowground tissue production of *S. patens* (Seneca 1974). Since the saltwater experiment was conducted from June 1977 thru November 1977, it could have been possible that diminishing photoperiod influenced belowground tissue production. Even if this were the case, the data on heavy metal uptake by the plants are still valid because the plants were all grown at the same time and subjected to the same photoperiod.

Total heavy metal content

166. The total heavy metal content of the saltwater sediments is presented in Table 32. The sediments used in this portion of the study were chosen because they were considered contaminated with heavy metals. Generally, total heavy metal content of the saltwater sediments varied from site to site as did the freshwater sediments. Similar ranges of most metals were found in both saltwater and freshwater sediments.

167. Zinc. Total zinc content of the saltwater sediments was site specific ranging from a low of 84 $\mu g\ g^{-1}$ to a high of 5523 $\mu g\ g^{-1}$. Two sediments (BER and CC 3) contained more zinc than that reported in the literature (Table 33). The other sediments had total zinc contents that were within the range of total zinc content of saltwater sediments reported in the literature (Table 33). These values appeared to be generally less than those reported in the literature for freshwater sediments used in this study.

168. Cadmium. Total cadmium content of the saltwater sediments was also site specific. Cadmium ranged from 4.9 $\mu g\ g^{-1}$ to 52.6 $\mu g\ g^{-1}$. The total cadmium content of the saltwater sediments was generally at or beyond the upper range of total cadmium contents of contaminated saltwater sediments reported in the literature (Table 34). These values appeared to be generally less than those reported for freshwater sediments used in this study.

169. Copper. The total copper content of the saltwater sediments ranged from 19 $\mu g\ g^{-1}$ to 1096 $\mu g\ g^{-1}$. The range of total copper content of the sediments was within that reported in the literature for contaminated saltwater sediments (Table 35) and was generally higher than that

Table 32

Concentration of Heavy Metals in Nitric Acid Digests of the Saltwater Sediments

Location*/	Concentration, $\mu g\ g^{-1}$									
Site	Zn	Cd	Cu	Fe**	Mn	As	Hg	Ni	Cr	Pb
BRH	838	25.4	1096	19.43	148	3.6	1.15	138.5	893.1	477.3
JNC	946	49.2	746	24.87	271	2.6	0.74	113.7	480.1	407.6
COL	783	43.6	397	29.60	368	29.3	0.49	50.0	363.1	346.5
BER	5523	52.6	646	92.30	513	26.6	1.24	78.2	4368.1	824.0
NWB	341	8.3	328	28.07	457	27.2	0.38	41.1	225.6	157.3
CC 1	95	7.3	19	10.73	482	10.2	0.11	11.6	7.9	23.1
2	278	8.2	25	10.43	477	1.3	0.32	11.8	20.5	43.6
3	3795	36.6	143	9.58	309	3.6	1.48	13.1	34.6	635.6
OH 1	223	10.3	226	32.00	407	1.0	0.75	94.5	107.3	126.0
2	345	10.8	101	28.48	293	3.8	0.72	76.0	79.1	162.8
3	294	6.7	99	15.40	171	2.7	0.36	48.3	56.1	218.0
SE 1	84	8.3	61	22.75	246	2.6	0.17	21.1	24.2	101.7
2	172	8.3	144	21.32	228	3.9	0.63	26.9	37.9	209.8
3	277	4.9	136	28.84	216	---	---	43.9	69.2	481.4
CV†	14	9.7	14	11.70	10	38.8	33.0	8.6	49.9	14.5

* Abbreviations are the same as those listed in Figures 2-4.
** Concentration of Fe is in mg g^{-1}.
† CV = coefficient of variation (%).

Table 33

Total Zinc Content of Some Saltwater Sediments

Concentration or Range $\mu g\ g^{-1}$	Literature Reference
14 - 84	Hallberg (1974)
30 - 35	Yu and Chen (1978)
53 - 168	Eisler et al. (1977)
57 - 110	Galloway (1979)
77 - 111	Drifmeyer and Odum (1975)
142 - 320	Skei and Paus (1979)
160	Christensen, Scherfig, Koide (1978)
234 - 1067	Brannon et al. (1976a, 1976b)
315 - 1550	Stoffers et al. (1977)
500	Sylvester and Ware (1977)

Table 34

Total Cadmium Content of Some Saltwater Sediments

Concentration or Range $\mu g\ g^{-1}$	Literature Reference
0.06 - 2.45	Eisler et al. (1977)
0.22 - 0.53	Galloway (1979)
1.0 - 1.5	Yu and Chen (1977)
1.4 - 52	Stoffers et al. (1977)
3.6 - 17.6	Brannon et al. (1976a, 1976b)
10	Sylvester and Ware (1977)

reported for the freshwater sediments used in this study.

170. Iron. Total iron content of the saltwater sediments was generally within that reported in available literature (5 mg g^{-1} to 71.0 mg g^{-1}) with the exception of iron in BER sediments (Table 36). The total iron contents of the sediments from this study ranged from 9.58 mg g^{-1} to 92.30 mg g^{-1}. These values were generally less than those found for the freshwater sediments used in this study.

Table 35

Total Copper Content of Some Saltwater Sediments

Concentration or Range $\mu g\ g^{-1}$	Literature Reference
1.3 - 22.1	Hallberg (1974)
5 - 10	Yu and Chen (1977)
13 - 21	Galloway (1979)
26 - 98	Eisler et al. (1977)
31	Skei and Paus (1979)
37 - 1117	Brannon et al. (1976a, 1976b)
40	Christensen, Scherfig, and Koide (1978)
117 - 3136	Stoffers et al. (1977)

Table 36

Total Iron Content of Some Saltwater Sediments

Concentration or Range $\mu g\ g^{-1}$	Literature Reference
5 - 47	Hallberg (1974)
12 - 15	Yu and Chen (1977)
15.0 - 71.0	Skei and Paus (1979)
20 - 27	Galloway (1979)
30 - 40	Eulenkeuser, Guess, and Willhorr (1974)
42.4 - 43.6	Brannon et al. (1976a, 1976b)
44	Christensen, Scherfig, and Koide (1978)

171. Manganese. Total manganese content of the saltwater sediments ranged from 148 $\mu g\ g^{-1}$ to 513 $\mu g\ g^{-1}$. The total manganese content of the sediments was generally within or slightly below that reported in the literature (Table 37). These values were generally less than those found in the freshwater sediments used in this study.

172. Arsenic. Total arsenic content of the saltwater sediments

Table 37

Total Manganese Content of Some Saltwater Sediments

Concentration or Range $\mu g\ g^{-1}$	Literature Reference
163 - 970	Drifmeyer and Odum (1975)
230 - 450	Galloway (1979)
380	Christensen, Scherfig, and Koide (1978)
531 - 746	Brannon et al. (1976a, 1976b)
840 -4900	Skei and Paus (1979)

ranged from 1.0 $\mu g\ g^{-1}$ to 29.3 $\mu g\ g^{-1}$. All but four of the sediments had total arsenic contents below 10.2 $\mu g\ g^{-1}$, which is well within the range reported in available literature (Table 38). Sediments from Baltimore had the highest total arsenic contents (26.6 to 29.3 $\mu g\ g^{-1}$), but were still within the range reported in the literature. The arsenic content of the saltwater sediments was approximately the same as that of the freshwater sediments used in this study with the exception of ME 3.

Table 38

Total Arsenic Content of Some Saltwater Sediments

Concentration or Range $\mu g\ g^{-1}$	Literature Reference
0.15 - 1.0	Waslenchuk and Windom (1978)
4.0 - 6.9	Brannon et al. (1976a, 1976b)
6 - 30	Skei and Paus (1979)

173. Mercury. The total mercury content of the saltwater sediments ranged from 0.11 $\mu g\ g^{-1}$ to 1.48 $\mu g\ g^{-1}$. The total mercury content of the saltwater sediments was within or below that reported in the

literature (Table 39). The mercury content of the saltwater sediments was generally higher than that of the freshwater sediments used in this study.

174. Nickel. Total nickel content of the sediments ranged from 11.6 to 138.5 $\mu g\ g^{-1}$ and was within the range of total nickel content of contaminated sediments (Table 40). The nickel content of the saltwater sediments was generally greater than that of the freshwater sediments used in this study.

Table 39

Total Mercury Content of Some Saltwater Sediments

Concentration or Range $\mu g\ g^{-1}$	Literature Reference
0.03 - 0.05	Yu and Chen (1977)
0.04 - 0.18	Skei and Paus (1979)
0.1 - 5.5	
0.5 - 9.0	Eganhouse, Young, and Johnson (1978)
0.52 - 1.12	Brannon et al. (1976a, 1976b)

Table 40

Total Nickel Content of Some Saltwater Sediments

Concentration or Range $\mu g\ g^{-1}$	Literature Reference
1.42 - 9.08	Hallberg (1974)
5 - 500	Knauer (1977)
6 - 34	Eisler et al. (1977)
15 - 20	Yu and Chen (1979)
34 - 46	Skei and Paus (1979)

175. Chromium. Total chromium content of the saltwater sediments ranged from a low of 7.9 $\mu g\ g^{-1}$ to a high of 4368 $\mu g\ g^{-1}$. This range in total chromium content exceeded that reported in the literature (Table 41).

Table 41

Total Chromium Content of Some Saltwater Sediments

Concentration or Range $\mu g\ g^{-1}$	Literature Reference
10 - 30	Yu and Chen (1977)
13 - 81	Eisler et al. (1977)
34 - 62	Galloway (1979)
78	Christensen, Scherfig, and Koide (1978)
218 - 2146	Stoffers et al. (1977)

Most of the sediments, however, had total chromium contents that were within the range of that reported in the literature.

176. Lead. Total lead content of the sediments ranged from 23.1 $\mu g\ g^{-1}$ to 824.0 $\mu g\ g^{-1}$. The total lead content of BER and CC 3 sediments was greater than that reported in the literature (Table 42). Sediments from BER and CC 3 were 824 $\mu g\ g^{-1}$ and 635.6 $\mu g\ g^{-1}$, respectively.

Table 42

Total Lead Content of Some Saltwater Sediments

Concentration or Range $\mu g\ g^{-1}$	Literature Reference
3.9 - 18.8	Hallberg (1974)
4.3 - 28.7	Tiravanti and Boari (1979)
6.2 - 10.0	Galloway (1979)
13.1 - 31.2	Drifmeyer and Odum (1975)
17 - 81	Eisler et al. (1977)
20 - 50	Yu and Chen (1977)
20 - 114	Skei and Paus (1979)
49	Christensen, Scherfig, and Koide (1978)
104 - 616	Stoffers et al. (1977)
200	Sylvester and Ware (1977)

177. In summary, the total heavy metal content of the saltwater sediments used in this study was generally within the range for saltwater sediments reported in the literature, except for cadmium and lead.

178. The saltwater sediments had zinc, cadmium, iron, and manganese contents less than those of the freshwater sediments used in this study. Copper, mercury, nickel, and lead content in saltwater sediments was higher than that in the freshwater sediments used in this study. Arsenic and chromium content of the saltwater sediments was about equal to that in the freshwater sediments used in this study.

DTPA extractable heavy metals

179. The concentration of heavy metals in DTPA extracts of original reduced saltwater sediments and of air-dried sediments is presented in Table 43. The difference in concentration of heavy metals in DTPA extracts between the two sediment conditions was determined using the Least Significant Difference method, probability $\alpha = 0.05$ ($LSD_{0.05}$). In order for the differences to be real (significantly different), they have to exceed the indicated LSD's.

180. Air drying the saltwater sediments had a greater effect on DTPA extractable zinc and cadmium than any of the other heavy metals. DTPA extractable lead and copper showed similar effects for certain sediments upon air drying. The zinc concentration in DTPA extracts of air-dried sediments was higher than that from original sediments in 12 out of 14 cases; that of copper was higher in air-dried sediments in 8 out of 14 cases. Extraction of the original sediments resulted in heavy metal concentrations equal to that of air-dried sediments for cadmium (10 of 14), iron (14 of 14), and nickel (9 of 14). No differences between air-dried and flooded sediments were found for DTPA extracted mercury.

181. The arsenic concentration in the air-dried sediments could not be determined because of chemical interference due to excessive salt levels in the saltwater sediments. The interference could not be overcome by dilution. This could imply that DTPA would not be the best choice for determining sediment arsenic.

182. Silviera and Sommers (1977) have suggested that if sludges

Table 43

Concentration of Heavy Metals in DTPA Extracts of Reduced (Flooded) and of Reconstituted, Air-Dried (Upland) Saltwater Sediments

Location*/ Site	Concentration, $\mu g\ g^{-1}$									
	Zn		Cd		Cu		Fe		Mn	
	Flooded	Upland	Flooded	Upland	Flooded	Upland	Flooded	Upland	Flooded	Upland
BRH	0.3	408.3	<0.0005	0.42	0.03	0.30	1579	853	8.5	23.5
JNC	0.9	803.2	<0.0005	28.54	0.27	0.14	1430	571	5.0	13.8
COL	0.3	455.3	<0.0005	32.34	0.04	0.33	1426	727	38.1	92.3
BER	0.1	954.0	<0.0005	15.94	<0.025	71.03	1334	159	7.0	36.4
NWB	0.6	134.2	<0.0005	2.06	0.06	40.31	1280	793	62.4	166.2
CC 1	10.8	93.2	<0.0005	1.16	0.81	6.78	548	159	183.4	164.1
2	54.1	305.5	0.22	3.27	0.03	11.66	481	128	232.0	181.8
3	5.6	1511.8	<0.0005	19.02	<0.025	0.13	1038	1	66.1	51.8
OH 1	4.5	125.4	0.86	2.08	<0.025	70.51	1259	526	60.9	50.4
2	1.0	166.9	<0.0005	1.96	<0.025	41.56	1329	672	33.9	52.4
3	70.7	168.4	0.38	0.75	6.1	47.12	1015	423	28.9	41.0
SE 1	5.6	67.5	0.18	1.01	<0.025	44.47	1300	508	14.1	17.7
2	3.1	128.5	<0.0005	2.30	<0.025	67.01	1359	511	7.3	17.8
3	0.1	111.6	<0.0005	2.03	0.07	50.69	1315	513	2.2	35.1
$LSD_{0.05}$**	85.1		7.39		17.10		118		23.1	

Location*/ Site	Concentration, $\mu g\ g^{-1}$									
	As		Hg		Ni		Cr		Pb	
	Flooded	Upland	Flooded	Upland	Flooded	Upland	Flooded	Upland	Flooded	Upland
BRH	<0.005	CI†	0.0026	0.0020	--	41.14	--	2.83	--	212.32
JNC	<0.005	CI	<0.001	<0.001	10.47	33.58	0.62	2.11	0.81	198.92
COL	0.3505	CI	<0.001	0.0011	6.31	6.21	0.57	1.26	1.62	47.56
BER	0.0750	CI	<0.001	0.0022	3.39	19.17	1.18	2.59	0.77	0.61
NWB	0.5189	CI	<0.001	0.0018	2.57	5.17	0.67	2.24	9.70	72.75
CC 1	0.2377	CI	<0.001	0.0016	0.20	0.50	<0.01	<0.01	4.63	14.07
2	0.2216	CI	<0.001	0.0013	0.47	0.27	0.08	<0.01	35.01	14.15
3	<0.005	CI	<0.001	0.0017	0.42	0.60	0.07	<0.01	41.10	388.31
OH 1	0.0096	CI	<0.001	0.0020	3.67	3.51	0.33	0.10	23.93	48.89
2	<0.005	CI	<0.001	0.0013	2.55	7.89	0.07	0.12	0.86	78.57
3	<0.005	CI	<0.001	0.0019	4.50	3.54	0.41	0.57	85.52	129.62
SE 1	<0.005	CI	<0.001	0.0019	0.94	1.81	0.61	0.17	60.85	92.73
2	0.2245	CI	<0.001	0.0017	1.20	2.92	0.20	0.29	28.28	181.52
3	0.1456	CI	0.0019	0.0002	1.05	8.42	0.25	0.58	0.80	240.07
$LSD_{0.05}$**	--		0.0029		1.79		0.12		16.33	

* Abbreviations are the same as those listed in Figures 2-4.
** $LSD_{0.05}$ = Least Significant Difference at $\alpha = 0.05$.
† CI = Chemical interference.

were air dried, DTPA extractable heavy metals would increase. They explained that the increase in DTPA extractable heavy metals was due to dissolution of metal precipitates, oxidation of metal sulfides, and release of metals complexed with sludge organic matter as the organic matter decomposed.

183. The relative high sulfur and organic matter content of the saltwater sediments could have resulted in release of heavy metals upon air drying the sediments and subsequent oxidation of metal sulfides and release from organic complexes. Dissolution of heavy metal precipitates could have resulted from decreased sediment pH as a result of sulfide oxidation (Patrick 1964).

184. The presence of sodium and potassium in the saltwater sediments would tend to increase the exchangeable amount of heavy metals that might be adsorbed to fine-textured particles. Consequently, more heavy metals would be extracted under air-dried conditions due to sodium and potassium interactions and exchanges with metals adsorbed to sediment particles. Both sodium and potassium ions are used in studying exchange reactions in soil chemistry studies.

185. The DTPA extraction data would suggest that availability and plant uptake of zinc, cadmium, copper, and lead would be greater when saltwater sediments are placed in an upland condition rather than in a flooded condition. However, plant uptake from upland sediment conditions to verify this was not determined because of the excess salinity problem discussed above.

Interstitial water extractable heavy metals

186. Heavy metal concentrations in IW from original flooded saltwater sediments were compared to heavy metal concentrations in reconstituted IW of air-dried sediments (Table 44). This comparison was made to see if air drying resulted in increased heavy metal concentrations in sediment IW. The effect of plant growth on heavy metal concentrations in the IW of the original flooded sediments was also evaluated by comparing heavy metal concentrations in the IW at the beginning and end of the plant growth period.

Table 44

Initial Concentrations of Heavy Metals in Interstitial Water from Reduced (Flooded) and Oxidized, Air-Dried (Upland) Saltwater Sediments

Location*/ Site	Concentration, µg cm^{-3} Zn Flooded	Zn Upland	Cd Flooded	Cd Upland	Cu Flooded	Cu Upland	Fe Flooded	Fe Upland	[illegible] Flooded	[illegible] Upland
BRH	<0.0001	3.74	0.0001	0.8558	0.0102	0.6858	0.42	0.24	0.15	2.47
JNC	<0.0001	12.71	<0.0001	3.9291	0.1222	1.2458	1.28	0.24	0.13	2.79
COL	0.06	6.13	0.0002	1.1491	<0.0001	2.3958	9.39	0.82	1.74	15.89
BER	0.01	169.25	0.0027	1.3458	0.0035	0.4638	12.42	1.27	0.31	22.56
NWB	0.01	2.31	<0.0001	0.1321	<0.0001	0.2745	1.33	0.14	2.49	27.36
CC 1	<0.0001	0.22	0.0002	0.0068	0.0025	0.0578	0.36	0.10	3.28	0.24
2	<0.0001	0.37	0.0006	0.1078	0.0005	0.0412	0.43	0.11	4.36	3.24
3	<0.0001	6.93	0.0004	1.7091	0.0042	0.5535	0.23	0.13	1.70	10.66
OH 1	0.02	0.25	0.0002	0.0156	0.0309	0.2565	1.97	0.20	1.62	3.88
2	<0.0001	0.33	0.0053	0.0516	0.0362	0.2402	0.69	0.17	0.97	2.19
3	0.02	0.49	0.0037	0.0398	0.0209	0.8188	0.33	0.11	0.63	2.85
SE 1	0.04	0.39	0.0008	0.0321	0.0132	0.1125	2.03	0.11	0.44	0.75
2	0.06	0.62	0.0769	0.0805	0.0506	0.7812	2.67	0.18	0.35	1.80
3	0.11	1.83	<0.0001	0.6518	0.0162	12.0192	0.42	0.25	0.19	1.92
$LSD_{0.05}$**	1.47		0.1264		0.7934		1.18		1.01	

Location*/ Site	Concentration, µg cm^{-3} As Flooded	As Upland	Hg Flooded	Hg Upland	Ni Flooded	Ni Upland	Cr Flooded	Cr Upland	Pb Flooded	Pb Upland
BRH	<0.0010	<0.0010	<0.0002	0.0017	--	3.184	--	0.166	--	0.086
JNC	0.0032	<0.0010	<0.0002	0.0048	0.003	3.107	0.023	0.144	0.002	0.057
COL	0.0500	0.0283	<0.0002	0.0134	0.527	0.646	0.035	0.122	0.002	0.067
BER	0.0028	0.0033	<0.0002	0.0002	0.030	4.577	0.033	0.589	0.000	0.054
NWB	0.0051	0.0005	<0.0002	0.0002	0.005	1.870	0.013	0.382	0.000	0.113
CC 1	<0.0010	0.0020	<0.0002	0.0002	0.001	0.014	0.015	0.061	0.001	0.020
2	<0.0010	0.0118	<0.0002	0.0002	0.006	0.016	0.021	0.039	0.002	0.007
3	<0.0010	0.0080	<0.0002	0.0030	0.013	0.014	0.016	0.024	0.001	0.153
OH 1	<0.0010	0.0237	<0.0002	0.0002	0.005	0.110	0.029	0.029	0.003	0.007
2	<0.0010	0.0088	<0.0002	0.0002	0.009	0.060	0.007	0.019	0.015	0.034
3	<0.0010	0.0070	<0.0002	0.0138	0.028	0.114	0.046	0.112	0.006	0.080
SE 1	<0.0010	0.0118	<0.0002	0.0002	0.007	0.021	0.010	0.027	0.001	0.027
2	<0.0010	0.0175	<0.0002	0.0230	0.003	0.036	0.014	0.051	0.003	0.015
3	<0.0010	<0.0010	0.0003	0.0002	0.010	0.473	0.014	0.056	0.001	0.029
$LSD_{0.05}$**	--		0.0040		0.335		0.023		0.020	

* Abbreviations are the same as those listed in Figures 2-4.

** $LSD_{0.05}$ = Least Significant Difference at $\alpha = 0.05$.

187. Air drying the saltwater sediments resulted in increased heavy metal concentrations in the IW in approximately half of the sediments for zinc and cadmium (7 out of 14), manganese (11 out of 14), chromium (9 out of 14), and lead (9 out of 14). Iron concentrations in IW were decreased in 6 out of 14 of the air-dried sediments. The concentrations of the other heavy metals were about equal for flooded and air dried. These results would suggest that zinc, cadmium, manganese, chromium, and lead availability and plant uptake would be greater from air-dried sediment than from original flooded sediment.

188. The effect of plant growth on heavy metal concentration in the IW of the original flooded sediments suggests that only iron and manganese increased in concentration by the end of the plant growth period (Tables 45-49). Cadmium and copper concentrations in IW appeared to decrease by the end of the growth period. The rest of the heavy metals either had the same concentration or decreased to below detectable limits.

189. The sediments *D. spicata* grew in appeared to have more iron and manganese in the IW at the end of the growth period than those supporting *S. alterniflora*. These results suggest that either *D. spicata* can increase IW concentrations of iron and manganese more effectively than *S. alterniflora* or *D. spicata* did not take up the iron and manganese available in the IW. Plant concentrations of iron (to be discussed below) indicate that *D. spicata* increased IW content of iron more so than *S. alterniflora* in certain sediments with a corresponding increase in tissue content of iron (Table 50, COL, NWB, OH 3, and SE 1). However, plant concentrations of manganese indicate that *D. spicata* did not take up the manganese available in the IW of COL, BER, NWB, and CC 1-3. Consequently, more manganese was found in IW of these sediments at the end of the growth period. On the other hand, *S. alterniflora* took up more manganese from the IW of these sediments than did *D. spicata* (Table 50).

190. These results further suggest that *D. spicata* may be more efficient in obtaining iron from certain sediments than *S. alterniflora*, whereas *S. alterniflora* may be more efficient in taking up manganese

Table 45

Heavy Metal Concentrations in the Interstitial Water of Reduced (Flooded) Sediments from Two Sites in Bridgeport Harbor (BRH and JNC), Connecticut

Location*/ Site	Sampling Period**	Species	Concentration, $\mu g\ cm^{-3}$						
			Zn	Cd	Cu	Fe	Mn	As	Hg
BRH	Initially	*S. alterniflora*	<0.004	0.0001	0.0102	0.42	0.15	CI†	<0.0002
		D. spicata	<0.004	0.0001	0.0102	0.42	0.15	<0.0010	<0.0002
	End	*S. alterniflora*	<0.004	<0.0001	<0.001	3.82	1.05	<0.0010	0.0009
		D. spicata	0.05	<0.0001	<0.001	6.77	1.69	<0.0010	0.0002
JNC	Initially	*S. alterniflora*	<0.004	<0.0001	0.1222	1.28	0.13	0.0032	<0.0002
		D. spicata	<0.004	<0.0001	0.1222	1.28	0.13	0.0032	<0.0002
	End	*S. alterniflora*	<0.004	<0.0001	<0.001	7.75	0.37	<0.0010	0.0005
		D. spicata	<0.004	<0.0001	<0.001	7.37	2.43	<0.0010	<0.0002

* Abbreviations are the same as those listed in Figures 2-4.
** Water samples were taken initially and at the end of the growth period.
† CI = chemical interference.

Table 46

Heavy Metal Concentrations in the Interstitial Water of Reduced (Flooded) Sediments from Three Sites in Baltimore Harbor (COL, BER, and NWB), Maryland

Location*/ Site	Sampling Period**	Species	Concentration, $\mu g\ cm^{-3}$ Zn	Cd	Cu	Fe	Mn	As	Hg
COL	Initially	*S. alterniflora*	0.06	0.0002	<0.001	9.39	1.47	0.0500	<0.0002
		D. spicata	0.06	0.0002	<0.001	9.39	1.47	0.0500	<0.0002
	End	*S. alterniflora*	0.05	<0.0001	<0.001	37.17	4.71	CI†	0.0011
		D. spicata	0.02	<0.0001	<0.001	247.23	29.77	CI	<0.0002
BER	Initially	*S. alterniflora*	0.01	0.0027	0.0035	12.42	0.31	0.0028	<0.0002
		D. spicata	0.01	0.0027	0.0035	12.42	0.31	0.0028	<0.0002
	End	*S. alterniflora*	0.01	<0.0001	<0.001	201.40	3.44	CI	0.0010
		D. spicata	0.03	<0.0001	<0.001	205.57	6.23	CI	<0.0002
NWB	Initially	*S. alterniflora*	0.01	<0.0001	<0.001	1.33	2.49	0.0051	<0.0002
		D. spicata	0.01	<0.0001	<0.001	1.33	2.49	0.0051	<0.0002
	End	*S. alterniflora*	<0.004	<0.0001	<0.001	80.83	14.30	CI	0.0002
		D. spicata	0.08	<0.0001	<0.001	180.23	26.00	CI	0.0002

* Abbreviations are the same as those listed in Figures 2-4.
** Water samples were taken initially and at the end of the growth period.
† CI = chemical interference.

Table 47

Heavy Metal Concentrations in the Interstitial Water of Reduced (Flooded) Sediments from Three Sites in the Corpus Christi (CC), Texas, Ship Channel

Location*/ Site	Sampling Period**	Species	Concentration, $\mu g\ cm^{-3}$						
			Zn	Cd	Cu	Fe	Mn	As	Hg
CC 1	Initially	*S. alterniflora*	<0.0001	0.0002	0.0025	0.36	3.28	CI†	<0.0002
		D. spicata	<0.0001	0.0002	0.0025	0.36	3.28	CI	<0.0002
	End	*S. alterniflora*	<0.0001	<0.0001	<0.001	0.07	2.72	CI	0.0016
		D. spicata	<0.0001	<0.0001	<0.001	3.10	13.39	CI	<0.0002
CC 2	Initially	*S. alterniflora*	<0.0001	0.0006	0.0005	0.43	4.36	CI	<0.0002
		D. spicata	<0.0001	0.0006	0.0005	0.43	4.36	CI	<0.0002
	End	*S. alterniflora*	<0.0001	<0.0001	<0.001	0.03	3.79	CI	0.0027
		D. spicata	<0.0001	<0.0001	<0.001	0.79	11.10	CI	0.0002
CC 3	Initially	*S. alterniflora*	<0.0001	0.0004	0.0042	0.23	0.70	CI	<0.0002
		D. spicata	<0.0001	0.0004	0.0042	0.23	0.70	CI	<0.0002
	End	*S. alterniflora*	0.16	<0.0001	<0.001	0.15	0.81	CI	0.0013
		D. spicata	0.16	<0.0001	<0.001	14.68	15.00	CI	0.0003

* Abbreviations are the same as those listed in Figures 2-4.
** Water samples were taken initially and at the end of the growth period.
† CI = chemical interference.

Table 48

Heavy Metal Concentrations in the Interstitial Water of Reduced (Flooded) Sediments from Three Sites in Oakland Inner Harbor (OH), California

Location*/ Site	Sampling Period**	Species	Concentration, μg cm^{-3}						
			Zn	Cd	Cu	Fe	Mn	As	Hg
OH 1	Initially	*S. alterniflora*	0.02	0.0002	0.0309	1.97	1.62	CI[†]	<0.0002
		D. spicata	0.02	0.0002	0.0309	1.97	1.62	CI	0.0002
	End	*S. alterniflora*	<0.004	<0.0001	<0.001	28.83	5.06	CI	0.0011
		D. spicata	<0.004	<0.0001	<0.001	41.40	9.45	CI	0.0002
OH 2	Initially	*S. alterniflora*	<0.004	0.0053	0.0362	0.69	0.97	CI	<0.0002
		D. spicata	<0.004	0.0053	0.0362	0.69	0.97	CI	<0.0002
	End	*S. alterniflora*	0.01	<0.0001	<0.001	34.00	3.53	CI	0.0009
		D. spicata	0.02	<0.0001	<0.001	60.63	9.16	CI	0.0005
OH 3	Initially	*S. alterniflora*	0.02	0.0037	0.0209	0.33	0.63	CI	<0.0002
		D. spicata	0.02	0.0037	0.0209	0.33	0.63	CI	<0.0002
	End	*S. alterniflora*	<0.004	<0.0001	<0.001	2.91	2.09	CI	0.0004
		D. spicata	<0.004	<0.0001	<0.001	17.69	11.12	CI	0.0004

* Abbreviations are the same as those listed in Figures 2-4.
** Water samples were taken initially and at the end of the growth period.
† CI = chemical interference.

Table 49

Heavy Metal Concentrations in the Interstitial Water of Reduced (Flooded) Sediments from Three Sites in the Duwamish Waterway, Seattle (SE), Washington

Location*/ Site	Sampling Period**	Species	Concentration, μg cm^{-3}						
			Zn	Cd	Cu	Fe	Mn	As	Hg
SE 1	Initially	*S. alterniflora*	0.04	0.0008	0.0132	2.03	0.44	CI†	<0.0002
		D. spicata	0.04	0.0008	0.0132	2.03	0.44	CI	<0.0002
	End	*S. alterniflora*	<0.004	<0.0001	<0.001	14.14	0.87	CI	0.0012
		D. spicata	<0.004	<0.0001	<0.001	32.27	5.93	CI	0.0005
SE 2	Initially	*S. alterniflora*	0.06	0.0769	0.0506	2.67	0.35	CI	<0.0002
		D. spicata	0.06	0.0769	0.0506	2.67	0.35	CI	<0.0002
	End	*S. alterniflora*	<0.004	<0.0001	<0.001	19.37	1.47	CI	0.0010
		D. spicata	0.01	<0.0001	<0.001	32.53	6.14	CI	0.0005
SE 3	Initially	*S. alterniflora*	0.11	<0.0001	0.0162	0.42	0.19	CI	0.0003
		D. spicata	0.11	<0.0001	0.0162	0.42	0.19	CI	0.0003
	End	*S. alterniflora*	0.05	<0.0001	<0.001	30.13	0.97	CI	0.0005
		D. spicata	<0.004	<0.0001	<0.001	4180.	4.45	CI	0.0004

* Abbreviations are the same as those listed in Figures 2-4.
** Water samples were taken initially and at the end of the growth period.
† CI = chemical interference.

Table 50

Concentration of Heavy Metals in Aboveground Tissue of *S. alterniflora* and *D. spicata* Grown in Saltwater Sediments

Location*/ Site	Concentration, $\mu g\ g^{-1}$									
	Zn		Cd		Cu		Fe		Mn	
	*Spart.***	*Dist.*†	*Spart.*	*Dist.*	*Spart.*	*Dist.*	*Spart.*	*Dist.*	*Spart.*	*Dist.*
BRH	23.0	16.1	0.11	0.47	3.43	4.65	53.2	83.8	73	28
JNC	28.3	27.9	0.25	0.22	9.49	5.52	46.8	65.6	78	77
COL	52.3	17.2	0.23	0.32	3.32	4.38	84.8	143.7	223	157
BER	28.7	12.8	0.10	0.10	1.80	1.84	235.0	186.6	118	45
NWB	44.8	24.4	0.26	0.47	2.70	7.21	108.0	210.4	386	243
CC 1	125.4	83.8	0.69	0.58	3.37	8.69	58.2	67.2	426	119
2	113.7	126.4	0.16	0.59	2.64	18.45	56.4	59.2	417	113
3	75.9	63.0	0.23	0.23	2.39	3.69	42.5	61.2	257	71
OH 1	36.3	13.5	1.03	0.26	4.57	5.62	59.8	72.4	174	144
2	57.8	23.5	0.09	0.11	3.27	5.31	42.4	80.2	137	108
3	57.6	41.7	0.06	0.35	3.72	9.05	55.6	113.2	111	142
SE 1	26.7	35.5	0.05	0.22	8.17	11.26	66.0	176.9	118	142
2	32.2	31.6	0.26	0.10	5.07	7.59	81.7	90.5	149	125
3	20.4	17.2	0.09	0.65	2.37	2.55	60.1	89.9	99	67
$LSD_{0.05}$††	14.7		0.46		7.73		41.5		35	

Location*/ Site	Concentration, $\mu g\ g^{-1}$									
	As		Hg		Ni		Cr		Pb	
	*Spart.***	*Dist.*†	*Spart.*	*Dist.*	*Spart.*	*Dist.*	*Spart.*	*Dist.*	*Spart.*	*Dist.*
BRH	<0.025	<0.025	0.017	0.010	0.315	0.500	0.087	<0.025	1.03	1.22
JNC	<0.025	<0.025	0.021	0.017	0.123	0.700	0.288	0.339	0.51	1.65
COL	<0.025	<0.025	0.024	0.010	0.123	0.458	0.431	<0.025	5.59	4.19
BER	<0.025	<0.025	0.032	0.006	0.065	0.267	0.556	0.404	0.58	2.83
NWB	<0.025	<0.025	0.013	0.015	0.090	0.733	0.581	0.203	0.78	3.62
CC 1	<0.025	<0.025	0.022	0.035	0.323	0.325	1.181	0.103	1.33	2.06
2	<0.025	<0.025	0.020	0.018	0.157	0.258	1.398	0.406	0.68	1.05
3	<0.025	<0.025	0.022	0.028	0.165	0.492	0.187	0.003	0.89	3.27
OH 1	<0.025	<0.025	0.019	0.024	0.165	0.358	0.044	0.775	0.63	1.75
2	<0.025	<0.025	0.016	0.018	0.065	0.375	<0.025	0.539	0.27	2.05
3	<0.025	<0.025	0.017	0.025	0.248	0.683	0.319	0.439	0.80	2.37
SE 1	<0.025	<0.025	0.013	0.008	0.907	0.525	0.304	0.303	0.65	1.47
2	<0.025	<0.025	0.021	0.013	0.132	0.333	0.354	0.326	0.63	1.53
3	<0.025	<0.025	0.026	0.013	0.373	0.325	0.387	<0.025	0.38	2.15
$LSD_{0.05}$††	--		0.017		0.255		0.603		1.12	

* Abbreviations are the same as those listed in Figures 2-4.
** *Spart.* = *Spartina alterniflora*.
† *Dist.* = *Distichlis spicata*.
†† $LSD_{0.05}$ = Least Significant Difference at α = 0.05.

from certain sediments than *D. spicata*.

Plant uptake of heavy
metals, aboveground tissue

191. Zinc in *S. alterniflora*. Zinc concentration in aboveground tissue of *S. alterniflora* ranged from 20.4 to 125.4 μg g^{-1}. The higher values were obtained from the Corpus Christi sediments. Zinc concentrations for *S. alterniflora* have been reported from dredged material disposal sites along the Atlantic and gulf coasts of the United States as ranging from 10 to 20 μg g^{-1} by Lee et al. (1978) and averaging 38.6 μg g^{-1} by Drifmeyer and Odum (1975). Lee et al. (1978) reported zinc concentrations in *S. alterniflora* on a dredged material disposal site at Corpus Christi, Texas, of 125 to 155 μg g^{-1}, which agrees well with the values in Table 50 for Corpus Christi sediments. Zinc concentrations in tissue of natural stands of *S. alterniflora* have been reported by Broome, Woodhouse, and Seneca (1973) to be 11 μg g^{-1} for plants sampled in North Carolina salt marshes and 17 μg g^{-1} for plants sampled in South Carolina marshes (Drifmeyer and Odum 1975). Gosselink, Hopkinson, Parrondo (1977) reported zinc in *S. alterniflora* to range from 6.0 to 23.8 μg g^{-1}. The zinc concentrations found in *S. alterniflora* grown in this study on contaminated sediments were generally higher than the values reported from natural stands. It is important to note that the sediments containing the highest total amounts of zinc, 5523 μg g^{-1} (BER) and 3739 μg g^{-1} (CC 3), were not the sediments that produced the highest plant contents of zinc. These data support the contention that total nitric acid digests of sediments are poor indicators of plant available zinc.

192. Zinc in *D. spicata*. Zinc concentrations in aboveground tissue of *D. spicata* ranged from 12.8 μg g^{-1} to 126.4 μg g^{-1}, with most values being less than 40 μg g^{-1}. The higher zinc contents were found in plants grown in Corpus Christi sediments. Lee et al. (1978) found zinc concentrations in *D. spicata* from dredged material disposal sites that were mostly in the 10- to 20-μg g^{-1} range. The *D. spicata* samples at the Corpus Christi disposal site contained zinc from 90 to 110 μg g^{-1}. Gosselink, Hopkinson, and Parrondo (1977) reported zinc concentration in

D. spicata to range from 11.4 to 20.0 μg g^{-1}. Other data on zinc concentrations in *D. spicata* could not be found in the literature.

193. Cadmium in *S. alterniflora.* Cadmium concentration in aboveground tissue of *S. alterniflora* ranged from 0.05 μg g^{-1} to 1.03 μg g^{-1}, with most values being less than 0.30 μg g^{-1}. Even though the total cadmium content of the BER sediment was 52 μg g^{-1}, plants grown in that highly contaminated sediment contained only 0.1 μg g^{-1} cadmium in aboveground tissue. These values were within cadmium concentrations found in *S. alterniflora* from dredged material disposal sites by Lee et al. (1978) of 0.2 μg g^{-1} or less. Dunstan, McIntire, and Windom (1975) found an average concentration in *S. alterniflora* of 0.61 μg g^{-1} in natural stands of *S. alterniflora* along six river systems in South Carolina and Georgia. These results indicate that the cadmium content of *S. alterniflora* grown on contaminated saltwater sediments is no higher than that of *S. alterniflora* grown in natural marshes.

194. Cadmium in *D. spicata.* Cadmium content of *D. spicata* ranged from a low of 0.10 μg g^{-1} to a high of 0.65 μg g^{-1}. These values compare well and were within the same range as those found by Lee et al. (1978), which was the only other reference on cadmium content of *D. spicata* found in the literature.

195. Copper in *S. alterniflora.* The copper content of *S. alterniflora* ranged from a low of 1.80 μg g^{-1} to a high of 9.49 μg g^{-1}. These values were only slightly higher than those for *S. alterniflora* found by Lee et al. (1978) of 7 μg g^{-1} or less; Gosselink, Hopkinson, and Parrondo (1977) of 3.6 to 6.4 μg g^{-1}; and Broome, Woodhouse, and Seneca (1973) of 2 to 4 μg g^{-1}. It appeared that the copper content of *S. alterniflora* grown in this study was not much different than that reported in the literature.

196. Copper in *D. spicata.* The copper content of *D. spicata* ranged from 1.84 μg g^{-1} to 18.45 μg g^{-1}. Most values, however, were below 10 μg g^{-1}. The copper content of *D. spicata* grown on the saltwater sediments was slightly greater than that found in several investigations. Lee et al. found a range of copper content in *D. spicata* on dredged material of 2 μg g^{-1} to 7 μg g^{-1}. Gosselink, Hopkinson, and Parrondo (1977)

determined that the copper content of *D. spicata* in Louisiana natural marshes was 5.2 μg g^{-1}.

197. Iron in *S. alterniflora.* The iron content of *S. alterniflora* varied from 42.4 μg g^{-1} to 235 μg g^{-1}, but was generally less than 60 μg g^{-1}. These values were somewhat lower than those found by Gosselink, Hopkinson, and Parrondo (1977) of 154.2 μg g^{-1} to 632.0 μg g^{-1} and Broome, Woodhouse, and Seneca (1975) of 832.0 μg g^{-1}. These data suggest that the iron content of *S. alterniflora* grown in the contaminated saltwater sediments was lower than that reported in the literature.

198. Iron in *D. spicata.* The iron content of *D. spicata* ranged from 59.2 μg g^{-1} to 210.4 μg g^{-1} with most values being less than 100 μg g^{-1}. These values were somewhat lower than those of Gosselink, Hopkinson, and Parrondo (1977) of 193.8 μg g^{-1} to 862.0 μg g^{-1}.

199. The iron content of *D. spicata* tended to be higher than that of *S. alterniflora* for all sediments except BER. As discussed earlier, *D. spicata* may be more efficient in taking up iron than *S. alterniflora.* This difference was not found by Gosselink, Hopkinson, and Parrondo (1977) in plants from Louisiana marshes.

200. Manganese in *S. alterniflora.* The manganese content of aboveground tissue of *S. alterniflora* ranged from 73 μg g^{-1} to 426 μg g^{-1}. These values are somewhat higher than those for manganese reported by Gosselink, Hopkinson, and Parrondo (1977) of 34.0 μg g^{-1} to 79.6 μg g^{-1} and Broome, Woodhouse, and Seneca (1975) of 3.33 μg g^{-1} to 69.33 μg g^{-1}.

201. Manganese in *D. spicata.* The manganese concentration of *D. spicata* ranged from 28 μg g^{-1} to 243 μg g^{-1}. These values are below those reported by Gosselink, Hopkinson, and Parrondo (1977) of 126.76 μg g^{-1} to 368.8 μg g^{-1} for *D. spicata* from Louisiana marshes.

202. *Spartina alterniflora* appears to be more efficient in taking up manganese than does *D. spicata.*

203. Arsenic. The arsenic concentration in *S. alterniflora* and *D. spicata* was below detectable limits (0.025 μg g^{-1}) in all plants on all sediments. Other data could not be found in the literature for comparison of arsenic concentration in these plant species.

204. Mercury in *S. alterniflora.* The mercury concentration in

S. alterniflora was very low and ranged from 0.013 μg g^{-1} to 0.032 μg g^{-1}. The mercury concentration in *S. alterniflora* in this study was much lower than the 0.44 μg g^{-1} found in *S. alterniflora* in natural marshes extending from South Carolina to Florida (Dunstan, McIntire, and Windom 1975).

205. Mercury in *D. spicata.* The mercury concentration in *D. spicata* was also very low and ranged from 0.006 μg g^{-1} to 0.035 μg g^{-1}. Other data could not be found in the literature to compare to the concentration of mercury in *D. spicata* from this study.

206. Nickel in *S. alterniflora.* The nickel concentration in *S. alterniflora* ranged from 0.065 μg g^{-1} to 0.907 μg g^{-1} with most values being below 0.320 μg g^{-1}. Lee et al. (1978) determined that the nickel concentration of *S. alterniflora* from dredged material disposal sites was mostly below 2 μg g^{-1}; they did report a few samples with nickel concentrations up to 8 μg g^{-1}, however.

207. Nickel in *D. spicata.* The nickel concentration in *D. spicata* ranged from 0.258 μg g^{-1} to 0.733 μg g^{-1}. Nickel concentration of *D. spicata* grown on dredged material disposal sites was approximately 1.0 μg g^{-1} (Lee et al. 1978).

208. While certain sediments contained up to 138.5 μg g^{-1} of nitric acid extractable nickel (BRH, Table 32), plants grown on these flooded saltwater sediments only contained 0.5 μg g^{-1} nickel or less. These data suggest that plant uptake of nickel from contaminated sediments in a flooded disposal environment should be minimal. Lee, Sturgis, and Landin (1976) suggested that both *S. alterniflora* and *D. spicata* did not readily translocate root-absorbed nickel to plant tops. The present study also suggests little uptake and translocation of nickel to plant tops.

209. Chromium in *S. alterniflora.* The chromium concentration in *S. alterniflora* ranged from <0.025 μg g^{-1} to 1.398 μg g^{-1} but most values were below 0.600 μg g^{-1}. These values agree well with the chromium content of *S. alterniflora* grown on dredged material disposal sites reported by Lee et al. (1978) of values being mostly below 1.5 μg g^{-1}.

210. Chromium in *D. spicata.* The chromium content of *D. spicata*

ranged from <0.025 μg g^{-1} to 0.775 μg g^{-1} with most values below 0.550 μg g^{-1}. These values also agree well with the chromium content of *D. spicata* grown on dredged material disposal sites reported by Lee et al. (1978).

211. Even though nitric acid digests of some sediments indicated chromium contents of up to 4368.1 μg g^{-1} (BER, Table 32), plant contents were very low, 0.5 μg g^{-1} or less. These data indicate very little plant uptake of chromium from the contaminated saltwater sediments placed in a flooded environment. These results agree quite well with those obtained in a hydroponic study by Lee, Sturgis, and Landin (1976) in which chromium was shown to accumulate in roots of *S. alterniflora* and *D. spicata* with very little translocation to plant tops.

212. Lead in *S. alterniflora*. The lead concentration in *S. alterniflora* ranged from 0.27 μg g^{-1} to 5.59 μg g^{-1} but most values were below 1.00 μg g^{-1}. The lead content of *S. alterniflora* grown on dredged material disposal sites ranged from near 0.2 μg g^{-1} to more than 30 μg g^{-1} (Lee et al. 1978); the majority of the samples had lead contents of less than 1 μg g^{-1}. Drifmeyer and Odum (1975) found lead concentrations in *S. alterniflora* of 5.1 μg g^{-1} in plants growing on dredged material disposal sites in Virginia and 1.9 μg g^{-1} in natural marshes nearly. Banus, Valieda, and Teal (1974) found lead concentrations in *S. alterniflora* that ranged from 12.3 μg g^{-1} to 23.2 μg g^{-1} in plants from contaminated sediments and 5.4 μg g^{-1} to 9.5 μg g^{-1} in plants from uncontaminated sediments.

213. Lead in *D. spicata*. The lead concentration in *D. spicata* ranged from 1.05 μg g^{-1} up to 4.19 μg g^{-1}. Lee et al. (1978) reported lead concentrations in *D. spicata* that were mostly below 1.0 μg g^{-1} in plants that were grown on a number of dredged material disposal sites along the Atlantic and gulf coasts.

214. Summary. In summary, the results presented above indicate that contaminated saltwater sediments can be placed in a flooded disposal environment and produce marsh plants with contents of cadmium, copper, nickel, chromium, and lead that approach the contents found in natural marshes. Zinc was the only heavy metal that plants took up in higher

concentration than that reported for natural marshes.

Total plant uptake of heavy metals

215. Total plant uptake of heavy metals by *S. alterniflora* and *D. spicata* is presented in Table 51. For a proper interpretation of heavy metal concentration data in plants, it is necessary to consider the growth of the plant. When plant growth is considered in combination with concentration data, the effects of dilution within the plant can be determined and the true nature of plant uptake and bioaccumulation can be observed.

216. Zinc. *Spartina alterniflora* was observed to contain high zinc concentrations and had higher total uptake of zinc than *D. spicata* for at least 7 out of the 14 saltwater sediments. Even though *S. alterniflora* showed lower total aboveground yield than *D. spicata* for plants grown in sediments from COL and BER (Table 31), the zinc concentration (Table 50) and total zinc uptake (Table 51) by *S. alterniflora* was higher than that by *D. spicata*. In addition, aboveground yield of *S. alterniflora* was not different from that of *D. spicata* on sediments from NWB, CC 1, OH 1, and OH 2, even though *S. alterniflora* contained higher concentration and higher total uptake of zinc than did *D. spicata*. In another example, *S. alterniflora* produced more plant material on sediments from SE 3 (Table 31) but contained less zinc than *D. spicata* (Table 50); therefore total zinc uptake was greater by *S. alterniflora* than by *D. spicata* (Table 51).

217. Manganese. *Spartina alterniflora* contained higher manganese concentrations (Table 50) and took up more manganese (Table 51) than did *D. spicata* by plants grown in sediments from COL, BER, NWB, CC 1, CC 2, and CC 3. In addition, even though there was no difference in plant manganese concentration, total uptake of manganese was greater by *S. alterniflora* than by *D. spicata* on sediments from OH 1, OH 2, and SE 3. These data indicate that the greater plant growth of *S. alterniflora* is important in plant accumulation of manganese than it was for *D. spicata*.

218. Lead. *Disticilis spicata* took up more lead than did *S. alterniflora* on 5 out of the 14 sediments (Table 51). In addition, *D. spicata* contained higher lead concentrations than *S. alterniflora* on

Table 51

Total Uptake (Concentration × Aboveground Yield) of Heavy Metals by *S. alterniflora* and *D. spicata* From Several Saltwater Sediments Grown Under a Reduced (Flooded) Environment

Location*/ Site	Total Uptake, μg pot^{-1}									
	Zn		Cd		Cu		Fe**		Mn**	
	Spart.†	*Dist.*††	*Spart.*	*Dist.*	*Spart.*	*Dist.*	*Spart.*	*Dist.*	*Spart.*	*Dist.*
BRH	430	164	2.1	4.3	64.2	46.2	1.0	0.8	1.4	0.4
JNC	644	597	5.6	4.6	218.7	117.5	1.1	1.4	1.8	1.7
COL	1466	598	6.5	11.2	95.8	153.0	2.4	5.1	6.4	5.5
BER	1542	762	5.5	6.0	97.1	110.9	12.5	11.5	6.3	2.7
NWB	694	285	4.1	5.5	41.7	84.6	1.7	2.4	5.9	2.8
CC 1	872	584	5.1	4.1	23.7	60.3	0.4	0.5	3.0	0.8
2	672	564	1.0	2.7	15.8	85.3	0.3	0.3	2.5	0.5
3	1087	739	3.2	2.7	34.3	43.1	0.6	0.7	3.7	0.8
OH 1	568	142	15.5	2.7	71.6	59.6	0.9	0.8	2.7	1.5
2	1879	530	3.0	2.5	106.4	120.8	1.4	1.9	4.4	2.5
3	592	381	0.6	3.1	38.1	81.9	0.6	1.0	1.1	1.3
SE 1	365	294	0.6	1.8	109.8	94.4	0.9	1.5	1.6	1.2
2	348	240	2.7	0.7	53.9	56.3	0.9	0.6	1.6	0.9
3	869	548	4.1	20.9	99.3	81.5	2.6	2.8	4.2	2.1
$LSD_{0.05}$‡	277		4.9		50.2		1.2		0.9	

Location*/ Site	Total Uptake, μg pot^{-1}									
	As		Hg		Ni		Cr		Pb	
	Spart.†	*Dist.*††	*Spart.*	*Dist.*	*Spart.*	*Dist.*	*Spart.*	*Dist.*	*Spart.*	*Dist.*
BRH	<0.001	<0.001	0.31	0.08	5.86	5.30	1.64	0.04	19.36	14.08
JNC	<0.001	<0.001	0.47	0.36	2.80	15.74	6.34	6.39	11.81	22.51
COL	<0.001	<0.001	0.72	0.35	3.55	16.06	12.58	0.0	17.10	145.58
BER	<0.001	<0.001	1.71	0.42	3.47	16.09	29.72	27.56	31.31	172.59
NWB	<0.001	<0.001	0.20	0.18	1.38	8.65	8.99	2.38	11.95	42.14
CC 1	<0.001	<0.001	0.14	0.25	2.23	2.23	8.21	0.77	8.71	14.20
2	<0.001	<0.001	0.12	0.08	0.93	1.18	8.36	1.88	3.99	4.65
3	<0.001	<0.001	0.31	0.31	2.34	5.91	2.57	0.03	12.52	39.52
OH 1	<0.001	<0.001	0.30	0.25	2.60	3.81	0.68	8.19	9.74	18.70
2	<0.001	<0.001	0.50	0.39	2.10	8.53	0.0	13.74	8.71	46.75
3	<0.001	<0.001	0.17	0.23	1.50	6.13	3.53	3.58	8.11	21.56
SE 1	<0.001	<0.001	0.18	0.07	12.13	4.41	4.16	2.32	8.87	12.28
2	<0.001	<0.001	0.22	0.10	1.46	2.40	3.57	2.15	6.70	11.06
3	<0.001	<0.001	1.11	0.41	16.78	10.82	17.72	0.0	16.33	69.30
$LSD_{0.05}$‡	--		0.29		7.22		10.51		29.02	

* Abbreviations are the same as those listed in Figures 2-4.

** Concentrations of Fe and Mn are in mg pot^{-1}.

† *Spart.* = *Spartina alterniflora*.

†† *Dist.* = *Distichlis spicata*.

‡ $LSD_{0.05}$ = Least Significant Difference at α = 0.05.

7 out of the 14 sediments (Table 50). Again, plant growth was shown to be an important factor in plant uptake of heavy metals.

219. The other heavy metals (cadmium, copper, and iron) showed mixed results and, consequently, few differences in total uptake of these heavy metals were present.

Relationships of plant heavy metal content to sediment characteristics

220. Lee et al. (1978) observed significant relationships between DTPA extractable heavy metals and plant heavy metal content. These relationships were developed for *S. alterniflora* and *D. spicata* grown on existing CE dredged material disposal sites. The equations that were developed by Lee et al. (1978) were tested in this study by incorporating the sediment DTPA extraction data into the equations to predict the heavy metal content of the plant leaf. The predicted plant leaf content was then compared to the observed plant content of the heavy metals found in the present study.

221. Very poor agreement between predicted and observed plant heavy metal content was found for all heavy metals. This is not surprising since the relationships developed by Lee et al. (1978) were observed for plants that were growing on dredged material disposal sites that ranged from completely flooded to nearly air-dried conditions (upland). Plants in the present study were grown exclusively under flooded conditions. Plant uptake of heavy metals for the freshwater plants was shown to be different under flooded versus upland conditions. In addition, the sediments used in the present study were more contaminated compared to the dredged material found at the existing CE disposal sites. Therefore, the relationships developed previously may not apply to the present data from plant growth in more contaminated sediments under completely flooded conditions.

222. Since the amounts of DTPA extractable metals may change from flooded to upland environments, an attempt was made to utilize both DTPA extractable metals from flooded and air-dried sediments. An average value of DTPA extractable metal was calculated from the flooded and air-dried sediment extractions. This value was used in the equations of

Lee et al. (1978). Again, the agreement between predicted and observed plant content of metal was very poor. Poor agreement could have been a result of the highly contaminated nature of the sediments used in this study, whereas the level of contamination was much lower in the CE dredged material disposal sites studied by Lee et al. (1978).

223. Since the previous relationships of Lee et al. (1978) did not appear to hold with the data from the present experiment, a stepwise multiple regression analysis was performed on all of the sediment characteristics measured to develop prediction relationships for plant content of heavy metals. The procedure used was similar to that used in the freshwater portion of this study.

224. As mentioned in the freshwater portion of this study, it should be pointed out that these relationships are not to be considered definitive. One limitation on the equations is due to the fact that a large number of parameters were determined on a relatively small number of plant and sediment samples. Also, as pointed out earlier, an inflated R^2 can occur from random chance alone.

225. As in the freshwater portion of this study, another possible weakness in these relationships is the presence of extreme values that would result in high linear relationships.

226. The above are some of the reasons that prediction of heavy metal content of plants is so complex and difficult. The reader should be aware of the possible influences from those limitations when developing relationships for heavy metal contents of marsh plants. Any relationships developed need to be verified through further experiments. Consequently, the equations in Table 52 should be verified before widespread application.

Table 52

Prediction Equations for Heavy Metal Leaf Concentration in *S. alterniflora* and *D. spicata*

Prediction Equation	Simple Coefficient of Determination, r^2	Partial-F	Coefficient of Determination, R^2
	Plant Leaf Concentration, Zn		
$\hat{Y}_{SA}$* = 31.35 + 0.30 × SEDCACO3	0.810	42.25	
+ 0.30 × DTPAWZN	0.217	2.49	0.838
$\hat{Y}_{DS}$** = 16.62 + 9.00 × SEDCACO3	0.825	83.57	
+ 0.48 × DTPAWZN	0.342	14.10	0.923
	Plant Leaf Concentration, Cd		
$\hat{Y}_{SA}$ = 0.384 + 0.740 × DTPAWCD	0.372	17.61	
+ 0.009 × SEDSILT	0.272	12.19	0.705
$\hat{Y}_{DS}$ = 0.473 + 0.001 × DTPAWMN	0.284	0.99	
− 0.0002 × DTPAWFE	0.224	0.72	
+ 165.8 × DTPAWHG	0.196	15.44	0.719

(Continued)

* SA = *S. alterniflora*.
** DS = *D. spicata*.

Table 52 (Continued)

Prediction Equation	Simple Coefficient of Determination, r^2	Partial-F	Coefficient of Determination, R^2
	Plant Leaf Concentration, Cu		
$\hat{Y}_{SA}$ = 2.625 + 1.625 × DTPAWOP4	0.275	2.76	
− 0.009 × DTPAWZN	0.016	0.09	
+ 0.00002 × DTPAWMN	0.085	0.001	0.283
$\hat{Y}_{DS}$ = 0.952 + 0.047 × DTPAWMN	0.490	18.53	
+ 0.66 × DTPAWZN	0.434	4.77	
+ 2.84 × DTPAWOP4	0.000	8.64	0.807
	Plant Leaf Concentration, Fe		
$\hat{Y}_{SA}$ = 337.8 + 0.002 × SEDOILGR	0.841	22.81	
− 0.006 × SEDSULF	0.620	4.49	
− 33.6 × SEDPH	0.626	2.59	0.890
$\hat{Y}_{DS}$ = 708.5 − 74.7 × SEDPH	0.445	3.09	
+ 0.002 × SEDOILGR	0.440	2.59	
− 0.009 × SEDSULF	0.348	2.36	0.575
	Plant Leaf Concentration, Mn		
$\hat{Y}_{SA}$ = 63.5 + 10.07 × SEDCACO3	0.911	6.55	
+ 1.72 × DTPADMN	0.536	80.54	0.944
$\hat{Y}_{DS}$ = 80.3 + 0.084 × DTPADMN	0.251	13.91	
− 13.11 × SEDCACO3	0.018	7.98	0.566

(Continued)

Table 52 (Concluded)

Prediction Equation	Simple Coefficient of Determination, r^2	Partial-F	Coefficient of Determination, R^2
	Plant Leaf Concentration, Ni		
$\hat{Y}_{SA} = 0.679 - 0.031 \times DTPAWNI$	0.114	1.26	
$- 0.002 \times DTPAWMN$	0.007	0.44	
$- 0.0002 \times DTPAWFE$	0.00001	0.15	0.170
$\hat{Y}_{DS} = -0.745 + 0.031 \times DTPAWNI$	0.273	2.78	
$- 0.001 \times DTPAWMN$	0.115	0.61	
$- 0.0003 \times DTPAWFE$	0.094	0.42	0.320
	Plant Leaf Concentration, Cr		
$\hat{Y}_{SA} = 2.38 - 0.001 \times DTPAWFE$	0.660	68.78	
$- 0.053 \times SEDCLAY$	0.082	18.51	0.873
$\hat{Y}_{DA} = 0.190 + 0.0004 \times DTPAWFE$	0.004	0.05	
$+ 0.0381 \times SEDCLAY$	0.323	5.32	0.329
	Plant Leaf Concentration, Pb		
$\hat{Y}_{SA} = 0.682 - 0.046 \times DTPADOP4$	0.293	4.57	
$+ 0.019 \times SEDCAROG$	0.366	2.36	
$- 0.003 \times SEDCACO3$	0.287	0.01	0.570
$\hat{Y}_{DS} = 2.455 - 0.041 \times SEDCAROG$	0.054	0.47	
$- 0.060 \times DTPADOP4$	0.020	0.29	
$+ 0.033 \times SEDCACO3$	0.015	0.04	0.030

(Sheet 3 of 3)

PART IV: CONCLUSIONS AND RECOMMENDATIONS

227. Contamination of many U. S. waterways is obvious. Toxic metals, pesticides, organic wastes, nutrients, etc., can move into the nation's waterways as a result of land drainage, controlled waste, and uncontrolled waste disposal. Many of these contaminants can be associated with suspended solids. They can accumulate in the sediments and form a significant contaminant sink at the bottom of the waterways. During subsequent dredging and disposal of this contaminated sediment, the relative availability and/or release of contaminants can pose a major concern to the environment. Open-water disposal of reduced (anaerobic) sediment results in the sediment being exposed to oxidizing (aerobic) conditions for only a short time; consequently, the sediment normally reverts to its original reduced state upon deposition under water. Intertidal placement of dredged sediment allows the reduced sediment to undergo little drainage and only a limited amount of oxidation, mainly at the sediment surface (sediment-water interface). Upland disposal of dredged sediment can ultimately allow the sediment to dry out and oxidize completely. Previous Dredged Material Research Program research has shown that the availability or release of certain contaminants in the dredged sediments is controlled by the degree of oxidation. Therefore, in order for CE District personnel to make environmentally informed decisions on which disposal alternative to use for contaminated dredged sediment, it is necessary to have an estimate of the relative availability of these contaminants in dredged sediment under each disposal environment.

228. A greenhouse study of the solubility, availability, and plant uptake of the heavy metals zinc, cadmium, copper, arsenic, mercury, iron, manganese, nickel, chromium, and lead was conducted at two extremes of oxidation/reduction conditions, namely reduced (flooded) and oxidized (upland). The study included 15 highly contaminated freshwater sediments and 14 highly contaminated saltwater sediments. The saltwater portion of the study was limited to the flooded condition because of excessively high interstitial water salinity as the sediment was air dried for the upland condition.

229. The freshwater sediments were collected from waterways in the Great Lakes area. The saltwater sediments were collected from the Atlantic and gulf coast areas. The sediments were collected and transported to the laboratory where each sediment was mixed thoroughly and divided in half. One half of the sediment was potted and maintained in a reduced (flooded) state; the other half was air dried and ground before being potted (oxidized, upland condition). *Cyperus esculentus* was grown from tubers planted in the freshwater sediments; *Spartina alterniflora* and *Distichlis spicata* were grown from seed planted in the saltwater sediments. All plants were allowed to grow to maximum vegetative yield. The moisture content of the upland sediments was maintained between field capacity and wilting point of the plant. The plants were harvested and analyzed for the heavy metals listed above.

230. Both the flooded and upland sediments were subjected to an organic extractant (DTPA) as a measure of plant availability of heavy metals. Heavy metals in the interstitial water from the flooded sediments were compared to heavy metals in interstitial water from reconstituted, air-dried sediments. The sediments were also subjected to a concentrated nitric acid digestion to provide an estimate of the total quantity of heavy metals present in the sediment. The sediments were subjected to other chemical and physical analyses to further characterize them.

231. The texture of most of the sediments was predominately silt loam. The sediments were found to have high contents of organic matter and oil and grease. The freshwater sediments contained fairly substantial calcium carbonate equivalents with resultantly high pH's, while the saltwater sediments have low calcium carbonate equivalents and lower pH's. Sediment contents of phosphorus and nitrogen were not significantly different from those normally found in soil or sediments. While the sulfur content of the freshwater sediments was somewhat lower than that normally found in soils and sediments, the sulfur content of the saltwater sediments was somewhat higher. The total heavy metal content of the sediments was within the range of other reported contaminated sediments.

232. Air drying the sediments increased DTPA extractable heavy metals, especially zinc, cadmium, copper, manganese, chromium, and lead. The DTPA was not reliable for determining sediment arsenic or mercury. Air drying the sediments resulted in higher concentrations of zinc. copper, manganese, nickel, chromium, and lead in interstitial water extracts than in interstitial water from the flooded sediments.

233. Air drying the freshwater sediments resulted in increased plant content of heavy metals but the increases were site specific. Plant content of cadmium was as high as 20 $\mu g\ g^{-1}$ in some of the plants grown in air-dried freshwater sediment. An increase in concentration of heavy metal in plant tissue due to depressed plant growth in plants grown in upland sediments was demonstrated and indicated that plant yield was an important factor in determining plant uptake of heavy metals in freshwater sediments. Upland sediment conditions resulted in increased cadmium content in tubers of *C. esculentus*.

234. Plant uptake of the heavy metals cadmium, copper, nickel, chromium, and lead by the saltwater marsh plants *S. alterniflora* and *D. spicata* was found to approach the contents of those metals in naturally occurring marsh plants. Zinc was the only heavy metal that the saltwater plants took up in higher concentration that was greater than that reported for natural marshes.

235. Plant yield was also shown to be an important factor in determining total plant uptake of heavy metals in saltwater sediments. *Spartina alterniflora* had both higher zinc and lead concentration and total uptake than did *D. spicata*. The other heavy metals showed mixed results with few differences in total uptake of those heavy metals.

236. The results of relating plant heavy metal content to sediment characteristics indicated that a combination of the characteristics associated primarily with the sediment organic fraction was related to plant content of heavy metals. This was apparent for both freshwater and saltwater sediments. Organic matter and its formation of complex compounds with heavy metals was postulated to be the mechanism that controlled plant uptake of heavy metals. The oxidation/reduction processes of a sediment ultimately control the rate of organic matter decomposition. As

organic matter decomposes, the less available heavy metal-organic complexes are rendered more available, especially to plants.

237. In sediments where a potential exists for plant uptake of heavy metals such as zinc and cadmium, it can be minimized by maintaining the sediments in a reduced flooded condition and not allowing the sediment to drain and dry out or to become oxidized. The exception is arsenic, which becomes less available when a sediment is allowed to dry and become oxidized.

238. The results of this investigation showed that plants can be used as indicators for heavy metal availability in contaminated sediments. *Cyperus esculentus* showed that plant uptake of heavy metals, expecially zinc and cadmium, for air-dried sediments was greater than that from flooded sediments. Plant uptake of the heavy metals zinc and cadmium can be kept to a minimum by keeping the sediments in a reduced environment. There is a need to develop a plant bioassay procedure that can give an estimate of the potential availability of contaminants in sediments. Since the results of this investigation showed that plant uptake of heavy metals was site specific, it is recommended that a plant bioassay be performed on the sediments in question to determine the availability of heavy metals contained in sediments. Results of the plant bioassay will assist CE District personnel in making environmentally informed decisions on dredged material disposal alternatives.

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APPENDIX A: ACRONYMS AND VARIABLES USED TO DEVELOP THE PREDICTION EQUATIONS

Acronym	Variable
DTPAWAS	DTPA extractable arsenic of original, reduced sediment, $\mu g\ g^{-1}$
DTPAWCD	DTPA extractable cadmium of original, reduced sediment, $\mu g\ g^{-1}$
DTPAWCU	DTPA extractable copper of original, reduced sediment, $\mu g\ g^{-1}$
DTPAWFE	DTPA extractable iron of original, reduced sediment, $\mu g\ g^{-1}$
DTPAWMN	DTPA extractable manganese of original, reduced sediment, $\mu g\ g^{-1}$
DTPAWZN	DTPA extractable zinc of original, reduced sediment, $\mu g\ g^{-1}$
DTPAWHG	DTPA extractable mercury of original, reduced sediment, $\mu g\ g^{-1}$
DTPAWOP4	DTPA extractable orthophosphate of original, reduced sediment, $\mu g\ g^{-1}$
DTPAWCR	DTPA extractable chromium of original, reduced sediment $\mu g\ g^{-1}$
DTPAWNI	DTPA extractable nickel of original, reduced sediment, $\mu g\ g^{-1}$
DTPAWPB	DTPA extractable lead of original, reduced sediment, $\mu g\ g^{-1}$
DTPAWIMN	DTPA extractable iron/manganese ratio of original, reduced sediment
DTPAWCDZ	DTPA extractable cadmium/zinc ratio of original, reduced sediment
DTPADAS	DTPA extractable arsenic of reconstituted, air-dried sediment, $\mu g\ g^{-1}$
DTPADCD	DTPA extractable cadmium of reconstituted, air-dried sediment, $\mu g\ g^{-1}$
DTPADCU	DTPA extractable copper of reconstituted air-dried sediment, $\mu g\ g^{-1}$
DTPADFE	DTPA extractable iron of reconstituted air-dried sediment, $\mu g\ g^{-1}$

Acronym	Variable
DTPADMN	DTPA extractable manganese of reconstituted air-dried sediment, $\mu g\ g^{-1}$
DTPADZN	DTPA extractable zinc of reconstituted air-dried sediment, $\mu g\ g^{-1}$
DTPADOP4	DTPA extractable orthophosphate of reconstituted, air-dried sediment, $\mu g\ g^{-1}$
DTPADHG	DTPA extractable mercury of reconstituted, air-dried sediment, $\mu g\ g^{-1}$
DTPADCR	DTPA extractable chromium of reconstituted, air-dried sediment, $\mu g\ g^{-1}$
DTPADPB	DTPA extractable lead of reconstituted, air-dried sediment, $\mu g\ g^{-1}$
DTPADNI	Sediment nickel of reconstituted, air-dried sediment, $\mu g\ g^{-1}$
DTPADIMN	DTPA extractable iron/manganese ratio of reconstituted, air-dried sediment
DTPADCDZ	DTPA extrable cadmium/zinc ratio of reconstituted air-dried sediment
INSTWSAL	Salt concentration in interstitial water (IW) from original reduced sediment, ppt
INSTWPH	pH of IW from original, reduced sediment
INSTWAS	Arsenic in IW from original, reduced sediment, $\mu g\ cm^{-3}$
INSTWCD	Cadmium in IW from original, reduced sediment, $\mu g\ cm^{-3}$
INSTWCU	Copper in IW from original, reduced sediment, $\mu g\ cm^{-3}$
INSTWFE	Iron in IW from original, reduced sediment, $\mu g\ cm^{-3}$
INSTWMN	Manganese in IW from original, reduced sediment, $\mu g\ cm^{-3}$
INSTWZN	Zinc in IW from original, reduced sediment, $\mu g\ cm^{-3}$
INSTWHG	Mercury in IW from original, reduced sediment, $\mu g\ cm^{-3}$
INSTWOP4	Orthophosphate in IW from original, reduced sediment, $\mu g\ cm^{-3}$
INSTWCR	Chromium in IW from original, reduced sediment, $\mu g\ cm^{-3}$
INSTWPB	Lead in IW from original, reduced sediment, $\mu g\ cm^{-3}$
INSTWNI	Nickel in IW from original, reduced sediment, $\mu g\ cm^{-3}$
INSTWK	Potassium in IW from original, reduced sediment, $\mu g\ cm^{-3}$
INSTWNA	Sodium in IW from original, reduced sediment, $\mu g\ cm^{-3}$
INSTWNH3	Ammonia in IW from original, reduced sediment, $\mu g\ cm^{-3}$

Acronym	Variable
INSTWNO3	Nitrate in IW from original, reduced sediment, $\mu g\ cm^{-3}$
INSTWIMN	Iron/manganese ratio in IW from original, reduced sediment
INSTWCDZ	Cadmium/zinc ratio in IW from original, reduced sediment
INSTDSAL	Salt concentration in IW from reconstituted, air-dried sediment, ppt
INSTDPH	pH of IW from reconstituted, air-dried sediment
INSTDAS	Arsenic in IW from reconstituted, air-dried sediment, $\mu g\ cm^{-3}$
INSTDCD	Cadmium in IW from reconstituted, air-dried sediment, $\mu g\ cm^{-3}$
INSTIDCU	Copper in IW from reconstituted, air-dried sediment, $\mu g\ cm^{-3}$
INSTDFE	Iron in IW from reconstituted, air-dried sediment, $\mu g\ cm^{-3}$
INSTDMN	Manganese in IW from reconstituted, air-dried sediment, $\mu g\ cm^{-3}$
INSTDZN	Zinc in IW from reconstituted, air-dried sediment, $\mu g\ cm^{-3}$
INSTDOP4	Orthophosphate in IW from reconstituted, air-dried sediment, $\mu g\ cm^{-3}$
INSTDHG	Mercury in IW from reconstituted, air-dried sediment, $\mu g\ cm^{-3}$
INSTDCR	Chromium in IW from reconstituted, air-dried sediment, $\mu g\ cm^{-3}$
INSTDPB	Lead in IW from reconstituted, air-dried sediment, $\mu g\ cm^{-3}$
INSTDNI	Nickel in IW from reconstituted, air-dried sediment, $\mu g\ cm^{-3}$
INSTDIMN	Iron/manganese ratio in IW from reconstituted, air-dried sediment
INSTDCDZ	Cadmium/zinc ratio in IW from reconstituted, air-dried sediment
SEDSAND	Percent sand in the sediment
SEDSILT	Percent silt in the sediment
SEDCLAY	Percent clay in the sediment
SEDPH	pH of the sediment at 2:1 solution/sediment ratio
SEDCACO3	Percent CaCO3 equivalent of the sediment
SEDOILGR	Oil and grease (O&G) concentration in the sediment, $\mu g\ g^{-1}$

Acronym	Variable
SEDSU[illegible]	Sediment sulfur concentration, μg g^{-1}
SEDNH3N	Sediment total Kjeldahl nitrogen (TKN) concentration, μg g^{-1}
SEDCAROG	Sediment organic matter/sediment O&G ratio
SEDCARSU	Sediment organic matter/sediment sulfur ratio
SEDCARN3	Sediment organic matter/sediment TKN ratio
HNO3AS	Total arsenic concentration in sediment, μg g^{-1}
HNO3CD	Total cadmium concentration in sediment, μg g^{-1}
HNO3CU	Total copper concentration in sediment, μg g^{-1}
HNO3FE	Total iron concentration in sediment, μg g^{-1}
HNO3MN	Total manganese concentration in sediment, μg g^{-1}
HNO3ZN	Total zinc concentration in sediment, μg g^{-1}
HNO3OP4	Total orthophosphate concentration in sediment, μg g^{-1}
HNO3HG	Total mercury concentration in sediment, μg g^{-1}
HNO3K	Total potassium concentration in sediment, μg g^{-1}
HNO3NA	Total sodium concentration in sediment, μg g^{-1}
HNO3CR	Total chromium concentration in sediment, μg g^{-1}
HNO3PB	Total lead concentration in sediment, μg g^{-1}
HNO3NI	Total nickel concentration in sediment, μg g^{-1}
HNO31MN	Ratio of total iron/total manganese concentration in sediment
HNO3DZ	Ratio of total cadmium/total zinc concentration in sediment
INSTFAS	Arsenic in IW from original, reduced sediment taken at harvest, μg g^{-1}
INSTFCD	Cadmium in IW from original, reduced sediment taken at harvest, μg g^{-1}
INSTFCU	Copper in IW from original, reduced sediment taken at harvest, μg g^{-1}
INSTFFE	Iron in IW from original, reduced sediment taken at harvest, μg g^{-1}
INSTFMN	Manganese in IW from original, reduced sediment taken at harvest, μg g^{-1}
INSTFZN	Zinc in IW from original, reduced sediment taken at harvest, μg g^{-1}

Acronym	Variable
INSTFOP4	Orthophosphate in IW from original, reduced sediment taken at harvest, $\mu g\ g^{-1}$
INSTFHG	Mercury in IW from original, reduced sediment taken at harvest, $\mu g\ g^{-1}$
INSTFPH	pH of IW from original, reduced sediment taken at harvest, $\mu g\ g^{-1}$
INSTFK	Potassium in IW from original, reduced sediment taken at harvest, $\mu g\ g^{-1}$
INSTFNA	Sodium in IW from original, reduced sediment taken at harvest, $\mu g\ g^{-1}$
INSTFTKN	TKN in IW from original, reduced sediment taken at harvest, $\mu g\ g^{-1}$
INSTFNH3	Ammonia in IW from original, reduced sediment taken at harvest, $\mu g\ g^{-1}$
INSTFNO3	Nitrate in IW from original, reduced sediment taken at harvest, $\mu g\ g^{-1}$
INSTFSAL	Salt content of IW from original, reduced sediment taken at harvest, $\mu g\ g^{-1}$
YAGLIVE	Yield of aboveground live plant material, g pot^{-1}
YSTUBBLE	Yield of stubble plant material, g pot^{-1}
YAGDEAD	Yield of aboveground dead plant material, g pot^{-1}
YAGTOTAL	Total aboveground yield, g pot^{-1}
YBGROOTS	Yield of roots, g pot^{-1}
YBGTUBER	Yield of tubers, g pot^{-1}
PLANTAS	Arsenic in aboveground live plant material, $\mu g\ g^{-1}$
PLANTCD	Cadmium in aboveground live plant material, $\mu g\ g^{-1}$
PLANTCU	Copper in aboveground live plant material, $\mu g\ g^{-1}$
PLANTFE	Iron in aboveground live plant material, $\mu g\ g^{-1}$
PLANTMN	Manganese in aboveground live plant material, $\mu g\ g^{-1}$
PLANTZN	Zinc in aboveground live plant material, $\mu g\ g^{-1}$
PLANTOP4	Orthophosphate in aboveground live plant material, $\mu g\ g^{-1}$
PLANTHG	Mercury in aboveground live plant material, $\mu g\ g^{-1}$

Acronym	Variable
PLANTCR	Chromium in aboveground live plant material, $\mu g\ g^{-1}$
PLANTPB	Lead in aboveground live plant material, $\mu g\ g^{-1}$
PLANTNI	Nickel in aboveground live plant material, $\mu g\ g^{-1}$
PLANTK	Potassium in aboveground live plant material, $\mu g\ g^{-1}$
PLANTNA	Sodium in aboveground live plant material, $\mu g\ g^{-1}$
PLANTNH3	Nitrogen in aboveground live plant material, $\mu g\ g^{-1}$
ROOTK	Potassium in root tissue, $\mu g\ g^{-1}$
ROOTNA	Sodium in root tissue, $\mu g\ g^{-1}$
ROOTOP4	Orthophosphate in root tissue, $\mu g\ g^{-1}$
ROOTNH3N	Nitrogen in root tissue, $\mu g\ g^{-1}$
TUBERAS	Arsenic in tuber tissue, $\mu g\ g^{-1}$
TUBERCD	Cadmium in tuber tissue, $\mu g\ g^{-1}$
TUBERCU	Copper in tuber tissue, $\mu g\ g^{-1}$
TUBERFE	Iron in tuber tissue, $\mu g\ g^{-1}$
TUBERMN	Manganese in tuber tissue, $\mu g\ g^{-1}$
TUBERZN	Zinc in tuber tissue, $\mu g\ g^{-1}$
TUBEROP4	Orthophosphate in tuber tissue, $\mu g\ g^{-1}$
TUBERHG	Mercury in tuber tissue, $\mu g\ g^{-1}$
TUBERCR	Chromium in tuber tissue, $\mu g\ g^{-1}$
TUBERPB	Lead in tuber tissue, $\mu g\ g^{-1}$
TUBERNI	Nickel in tuber tissue, $\mu g\ g^{-1}$
TUBERNH3	Nitrogen in tuber tissue, $\mu g\ g^{-1}$
PLTUPAS	Total plant uptake (PLANTAS × YAGTOTAL) of arsenic, $\mu g\ pot^{-1}$
PLTUPCD	Total plant uptake (PLANTCD × YAGTOTAL) of cadmium, $\mu g\ pot^{-1}$
PLTUPCU	Total plant uptake (PLANTCU × YAGTOTAL) of copper, $\mu g\ pot^{-1}$
PLTUPFE	Total plant uptake (PLANTFE × YAGTOTAL) of iron, $\mu g\ pot^{-1}$
PLTUPMN	Total plant uptake (PLANTMN × YAGTOTAL) of manganese, $\mu g\ pot^{-1}$
PLTUPOP4	Total plant uptake (PLANTOP4 × YAGTOTAL) of orthophosphate, $\mu g\ pot^{-1}$
PLTUPHG	Total plant uptake (PLANTHG × YAGTOTAL) of mercury, $\mu g\ pot^{-1}$
PLTUPCR	Total plant uptake (PLANTCR × YAGTOTAL) of chromium, $\mu g\ pot^{-1}$

Acronym	Variable
PLTUPPB	Total plant uptake (PLANTPB × YAGTOTAL) of lead, μg pot^{-1}
PLTUPNI	Total plant uptake (PLANTNI × YAGTOTAL) of nickel, μg pot^{-1}
PLTUPK	Total plant uptake (PLANTK × YAGTOTAL) of potassium, μg pot^{-1}
PLTUPNA	Total plant uptake (PLANTNA × YAGTOTAL) of sodium, μg pot^{-1}
PLTUPNH3	Total plant uptake (PLANTNH3 × YAGTOTAL) of nitrogen, μg pot^{-1}
RUTUPK	Total root uptake (ROOTK × YBGROOTS) of potassium, μg pot^{-1}
RUTUPNA	Total root uptake (ROOTNA × YBGROOTS) of sodium, μg pot^{-1}
RUTUPOP4	Total root uptake (ROOTOP4 × YBGROOTS) of orthophosphate, μg pot^{-1}
RUTUPNH3	Total root uptake (ROOTNH3 × YBGROOTS) of nitrogen, μg pot^{-1}
TUBUPAS	Total tuber uptake (TUBERAS × YBGTUBER) of arsenic, μg pot^{-1}
TUBUPCD	Total tuber uptake (TUBERCD × YBGTUBER) of cadmium, μg pot^{-1}
TUBUPCU	Total tuber uptake (TUBERCU × YBGTUBER) of copper, μg pot^{-1}
TUBUPFE	Total tuber uptake (TUBERFE × YBGTUBER) of iron, μg pot^{-1}
TUBUPMN	Total tuber uptake (TUBERMN × YBGTUBER) of manganese, μg pot^{-1}
TUBUPZN	Total tuber uptake (TUBERZN × YBGTUBER) of zinc, μg pot^{-1}
TUBUPOP4	Total tuber uptake (TUBEROP4 × YBGTUBER) of orthophosphate, μg pot^{-1}
TUBUPHG	Total tuber uptake (TUBERHG × YBGTUBER) of mercury, μg pot^{-1}
TUBUPCR	Total tuber uptake (TUBERCR × YBGTUBER) of chromium, μg pot^{-1}
TUBUPPB	Total tuber uptake (TUBERPB × YBGTUBER) of lead, μg pot^{-1}
TUBUPNI	Total tuber uptake (TUBERNI × YBGTUBER) of nickel, μg pot^{-1}
TUBUPNH3	Total tuber uptake (TUBERNH3 × YBGTUBER) of nitrogen, μg pot^{-1}

In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Folsom, Bobby L.
Influence of disposal environment on availability and plant uptake of heavy metals in dredged material / by Bobby L. Folsom, Jr., Charles R. Lee, Derrick J. Bates (Environmental Laboratory, U.S. Army Engineer Waterways Experiment Station). -- Vicksburg, Miss. : The Station ; 1981.
151, 8 p. : ill. ; 27 cm. -- (Technical report / U.S. Army Engineer Waterways Experiment Station ; EL-81-12)
Cover title.
"December 1981."
Final report.
"Prepared for Office, Chief of Engineers, U.S. Army."
Bibliography: p. 141-151.

1. Aquatic plants. 2. Dredging spoil. 3. Heavy metals. 4. Plants, Effect of heavy metals on. I. Lee, Charles R. II. Bates, Derrick J. III. United States. Army. Corps of Engineers. Office of the Chief of Engineers.

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Influence of disposal environment on availability : ... 1981.
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IV. U.S. Army Engineer Waterways Experiment Station. Environmental Laboratory. V. Title VI. Series: Technical report (U.S. Army Engineer Waterways Experiment Station) ; EL-81-12.
TA7.W34 no.EL-81-12